DIELECTROPHORESIS OF SOLIDS IN AQUEOUS SOLUTIONS

By

KATHERINE WEI-LAN LOO CHEN

Bachelor of Science

Sam Houston State College

Huntsville, Texas

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DIELECTROPHORESIS OF SOLIDS IN AQUEOUS SOLUTIONS

Thesis Approved:

Herbert A. Pohl
Thesis Adviser

D. D. Durham
Dean of the Graduate College

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CHAPTER I

INTRODUCTION

"Dielectrophoresis" is defined as the motion of matter caused by polarization effects in a non-uniform electric field. Most polar materials move toward the place of greatest field intensity. Unlike electrophoresis this does not require a net charge on the particles[1].

Much work has been done in the past using dielectrophoretic force to separate solids from mixtures[2], to separate living and dead yeast cells, and in the investigation of dielectrophoresis of solids in aqueous media[3]. As a continuation of the latter work, it is the object of this paper to explain some of the anomalous results by investigating systematically the effects of:

(1) introducing ions of different valencies into the solution, and

(2) conductivity of both solid and liquid on dielectrophoresis.

If a uniform electric field is applied to a system containing a liquid dielectric and a suspended dielectric particle, the particle will polarize, but the net force (except possibly for a torque) on the particle will be zero. However, if the particle is charged, there will be a net force on the particle causing it to tend to migrate towards the oppositely charged terminal. The situation is different in a non-uniform field: here, the charged particles will again migrate in the direction depending on the particular charge of the particle, but this time the neutral particle will also experience a force. If the body is a perfect insulator and is more polar than the medium, according to simple dielectric theory, it will migrate toward the higher field region. The force equation[1] can be shown to be:

$$\vec{F} = 2\pi R^3 K_1 \varepsilon_0 \left(\frac{K_2 - K_1}{K_2 + 2K_1} \right) \vec{\nabla} \mid \vec{E} \mid^2 \qquad (1)$$

where R is the radius of the particle, K_2 is the dielectric constant of the particle, K_1 is the dielectric constant of the medium, and $\vec{E}$ is the applied electric field. Since the force depends on the square of the impressed field, the sign of the field is immaterial, therefore, alternating electric fields are used. It should be carried in mind that the force equation derived from the above simple theory was based on the assumptions that the particles are perfect dielectric particles in perfect dielectric liquids and such conditions are not experimentally observed. For instance, as in the work of Hawk and others[3], it was observed that lead hafnate with a dielectric constant of 350 moves away from the region of higher field intensity when in distilled water of dielectric constant of 80.

In trying to explain such anomalies, it is thought that perhaps at the solid-liquid interface, there exists an electrical double layer which effectively changes the polarization of the particle as well as the liquid around the interface. To test whether this double layer effect exists or not, cations and anions of different valencies were introduced systematically into the solution at controlled concentrations. If this double layer effect indeed exists, the motion of the particle should vary with the introduction of different ions.

Since conduction is a frequency dependent process, a more complete theory of the dielectrophoretic behaviour of lossy-dielectrics in lossy media was treated by Hawk, _et al_.[3] It is the purpose of this paper to re-check its degree of applicability.

To sum up, this thesis describes a systematic study of the effect of ions on the dielectrophoresis of solids, including tests for the existence of the double layer effect at the solid-liquid interface. It concludes with a discussion of the role played by it in the dielectrophoresis of solids.

CHAPTER II

THEORY

The Double Layer Theory

H. von Helmholtz (1879) suggested that an electrical double layer is generally formed at the separation of two phases. He treated the problem mathematically by assuming the double layer to be virtually an electrical condenser with two parallel plates separated by not more than a molecular distance. The potential gradient, according to Helmohltz's supposition, should be sharp at the interface, but a diffused double layer proposed by G. Gouy (1909) and others was later more favored[4]. O. Stern (1924) developed a view taking the essential characteristics of both and has shown that neither the sharp nor diffuse double layer theory alone was adequate. He divided the double layer into two parts. The first part was considered to be a fixed layer, which was only a single ion in thickness. In this part, there is a sharp fall of potential. The second part is the diffuse layer extending to some distance into the liquid; in this region, ions are free to move owing to thermal agitation but the distribution of ions is not uniform, since the charged layer at the surface will result in a preferential attraction of those of opposite sign. This causes a gradual fall of potential into the bulk of the liquid where the charge distribution is uniform. The situation at the solid-liquid interface may be represented diagrammatically by Figure 1 (parts I and II). The shaded part represents the solid and the

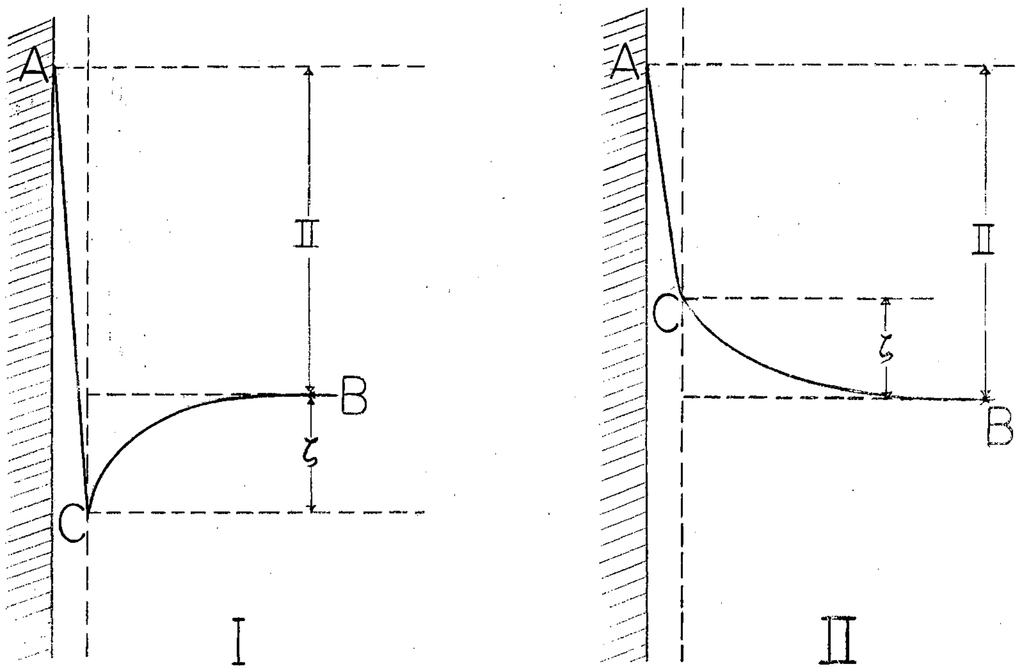


Figure 1. Electrokinetic Potential at the Solid-Liquid Interface

vertical broken line represents the distance of the fixed layer from the solid, the distance is somewhat exaggerated in the diagram. If A indicates the potential of the solid and B the potential of the bulk of the solution, then the potential in between can occur in two ways, (Figure 1, Parts I and II), depending on the characteristics of molecules or ions present in solution which make up the outer portion of the fixed layer. In both diagrams AC is the sharp fall of potential in the fixed part, and CB the gradual change in the diffuse part of the double layer. Between C and B, that is, between the fixed and freely mobile portions is marked ζ in each diagram, conventionally known as the zeta-potential.

By assuming that the double layer is equivalent to a parallel plate capacitor with plates separated by a distance d cm, each carrying a charge $|e|$, per square cm; the difference of potential between may be taken as equal to the zeta-potential, one may apply simple mathematical considerations to the electrokinetic phenomena. If D is the dielectric constant of the medium between the hypothetical plates, then it is well-known from electrostatics that

$$\zeta = \frac{4\pi ed}{D} \tag{2}$$

For all types of electrokinetic phenomena, this is a fundamental equation for the quantitative treatment.

Electrolytes and the Zeta-Potential

Substances which do not ionize in water are usually found to be negatively charged in contact with water, and the addition of small amounts of uniunivalent electrolyte tends to increase this charge. In the cases of negative zeta-potential, it is believed that hydroxyl ions from water and possibly also anions from the electrolyte are attached to the solid. An equal number of positive ions will remain in the liquid, some closely held in the fixed part of the double layer, and the rest in the diffused portion. The fall of potential from the solid to the bulk of the solution is shown diagrammatically in Figure 2, curve I.

If the concentration of the electrolyte is increased, there will be a tendency for the cations to accumulate on the solution side of the fixed double layer, i.e., in the vicinity of the dotted line XY in Figure 2. At one time, it was thought that the sole effect of this accumulation was a decrease of the charge density e, but now it seems to be established that the thickness d of the double layer is decreased simultaneously. From equation (2), we see that a decrease either d or e, or both, will result in a decrease of zeta-potential, as depicted in

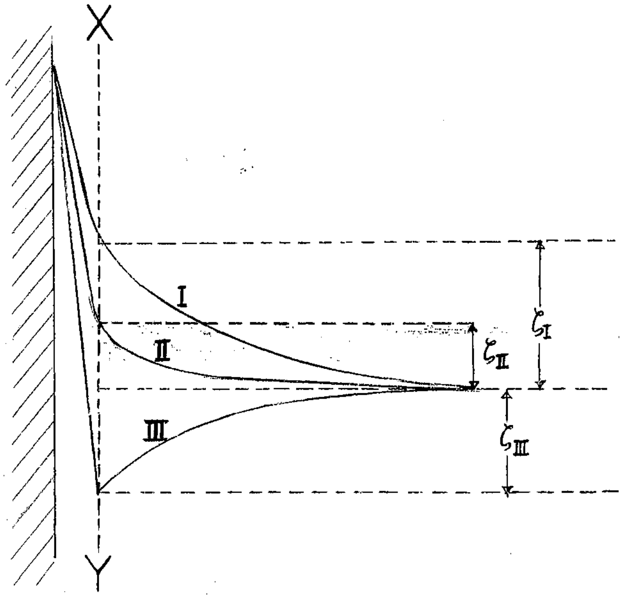


Figure 2. Diagrammatic Representation of the Effect of Ions on the Zeta Potential

Figure 2, II. The higher the valence of the cation, the lower the concentration of the solution required to bring about sufficient change in the adsorption layer to produce a given effect. If one increases the positive ion concentration, the sign of the electrokinetic potential may eventually be reversed; this is due to the neutralization of the charge on the particle or perhaps, to the decrease of the thickness of the double layer, to such an extent that it collapses and the double layer is reformed with the charges reversed (see Figure 2, III).

Hydroxyl and hydrogen ions, large organic ions and ions of heavy metals all are known to have a tendency to adsorb to neutral substances, such as carbon. They usually have a great influence on the electrokinetic potential. It was assumed that the potential of the solid in

Figure 2 remains unchanged, this is not necessarily true, for the strongly adsorbable positive ions present will tend to make it more positive and this will favor still further the decrease and eventual reversal of the zeta-potential.

It was experimentally observed that the zeta-potential tends in every case toward zero when the concentration of the electrolyte is increased. The exact significance of this fact is not yet clear; it may be due to the decrease in thickness of the double layer, because of the potential becoming very small, or it may be that the potential is appreciable but the observed electrokinetic effects are small owing to changes in the diffuse boundary layer and of the viscosity and dielectric constant of the liquid in that layer.

According to Sher [5], for a small lossy dielectric solid, the dielectrophoretic equation of force should be:

$$\vec{F} = \frac{3}{2} V_1 \, \text{Real} \left\{ \widetilde{\varepsilon_1^*} \left(\frac{\varepsilon_2^* - \varepsilon_1^*}{2\varepsilon_1^* + \varepsilon_2^*} \right) \vec{\nabla} \, | \, \vec{E}_o \, |^2 \right\}$$

where

$$\varepsilon^* = \varepsilon' - i \frac{\sigma}{\omega}$$

ε' is the dielectric constant

σ is the specific conductivity

ω is the angular frequency

V_1 is the volume of the solid.

If it is hypothesized that the effect due to the production of the double layer at the solid-liquid interface is included in ε', the real part of ε^*, one would expect it to reveal its effect most efficiently if low conductivity (i.e. high resistivity) and if high frequencies were used. This will be further discussed in Chapter V.

CHAPTER III

EXPERIMENTAL

Two new pieces of apparatus were constructed:

1. The platinum resistance probe,

2. The platinum plate-wire electrode cell.

The platinum resistance probe was used to measure the resistances of solutions. It consists of two shiny Pt plates which are enclosed and protected from being mispositioned by a Delrin (polyacetal) rod in the manner as shown in Figure 3. The connecting wires to the Pt plates are insulated from each other by Ambroid cement at the upper part of the rod. The two tiny tubes for the connecting wires to go through are filled with epoxy to insulate and to keep liquid from flowing into the tubes. The resistivity of the medium can be calculated from the geometric constants of the probe and the resistance measured on the bridge by the relation

$$\rho = \frac{A}{d} R \tag{3}$$

where

ρ = resistivity of the medium

R = resistance of the medium

A = area of the platinum plate

d = distance between the two plates

Since A and d are difficult to measure, ρ of the medium can always

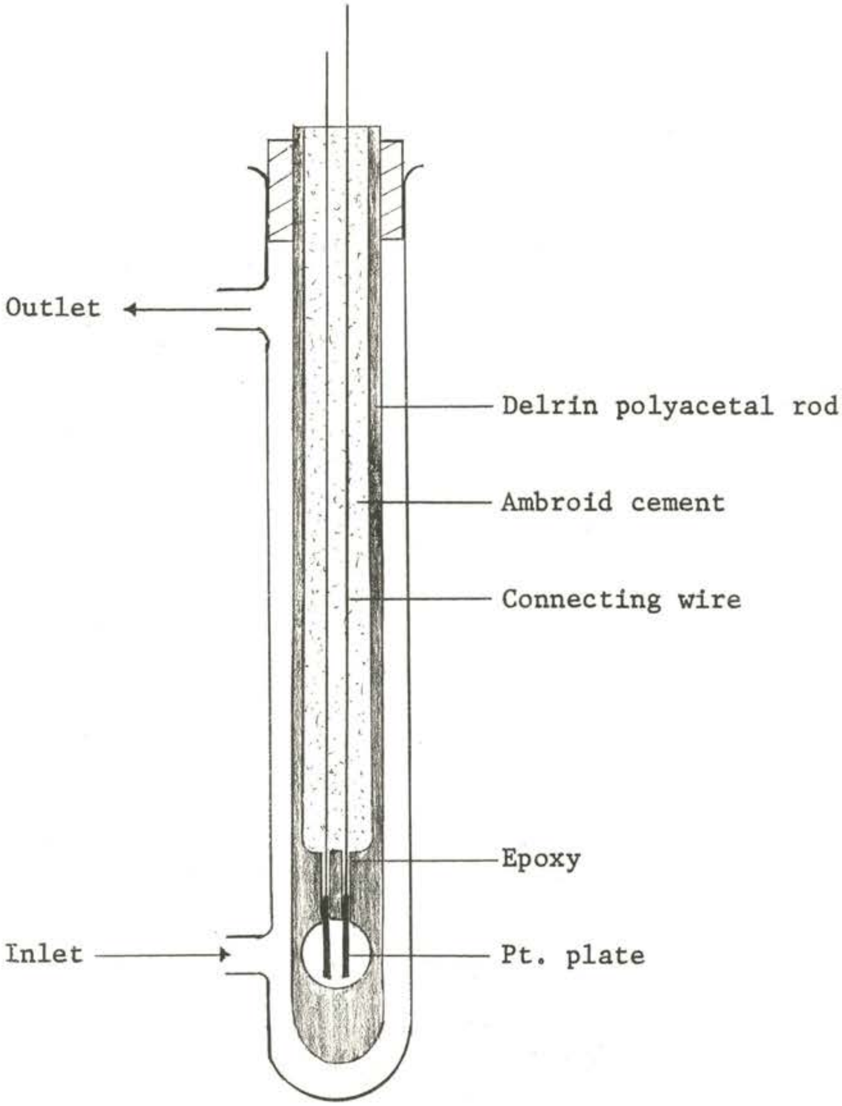
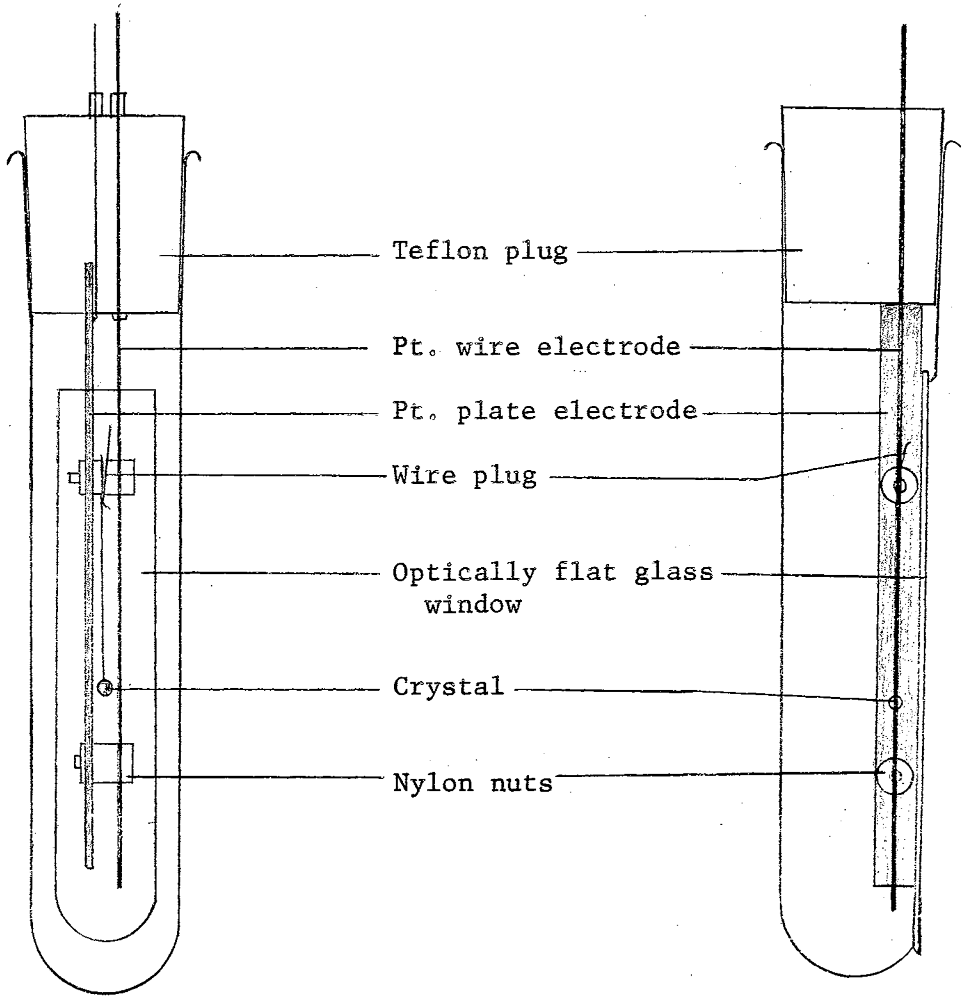


Figure 3. Platinum Resistance Probe



Front View

Side View

Figure 4. Platinum Plate-Wire Cell

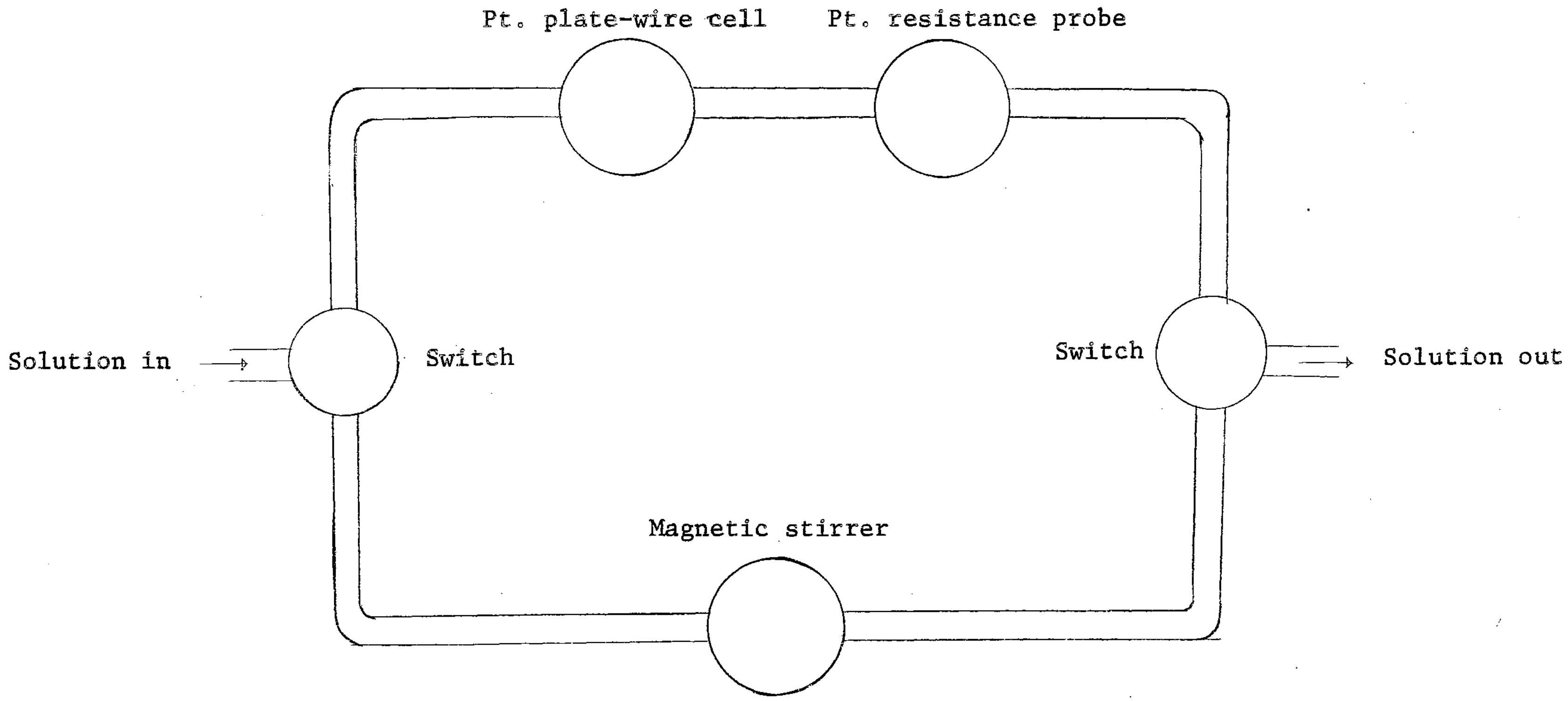


Figure 5. Schematics of Circulating System

be calculated from the relation:

$$\rho = \rho_1 \frac{R}{R_1} \tag{4}$$

where

ρ_1 = standard resistivity of 10^{-4} N KCl solution

R_1 = measured resistance of the same solution

The Pt plate-wire cell consists of a platinum plate about 125 mm x 6 mm as one electrode and a platinum wire(20 Gauge B & S)of about 200 mm in length and 1 mm in diameter. They are held in place by a teflon plug and two nylon nuts such that the distance of separation was about 2 mm (see Figure 4).

A rounded crystal was hung by a fiber through a minute hole on the higher nylon nut. It was made spherical by the centrifuge polisher constructed earlier[6]. It was cemented to a fine glass fiber by a minimum amount of epoxy resin. The cementing process was done under a binocular microscope and with a micro-manipulator. The fiber and the crystal were hung in place on the nylon nut by a wire plug. (See Figure 4.)

A magnetic stirrer together with these two pieces of apparatus were connected by rubber tubing in series, and with two stopcocks leading from the circulatory system into which our solutions are introduced. (See Figure 5).

The resistance of the medium was measured by a General Radio Co. Impedance Bridge, type 1650-B, with a precision of ± 1%. The null-point on the bridge was improved greatly by the inclusion of a decade capacitor, type 1412 BC, which had a range

$$1\rho F \leftrightarrow 1\mu F \ .$$

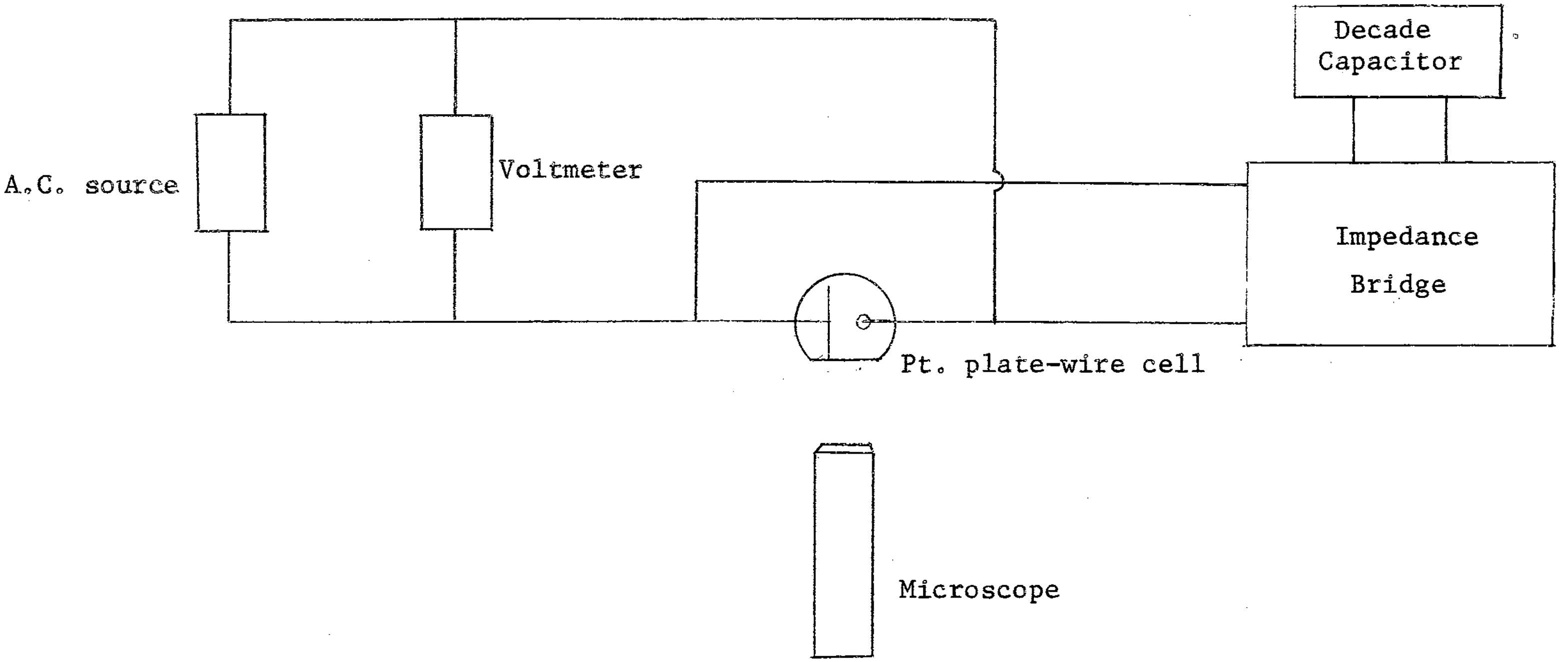


Figure 6. Schematic Diagram of Measuring Apparatus

The motion of the crystal in the platinum plate-wire cell was observed from the side through a Monolux microscope with the arm bent 90° from the vertical position. Both the cell and the microscope are mounted on a steel plate 60 cm x 20 cm x 1 cm which had three leveling-screws. By adjusting these screws the crystal could be placed at any initial position between the plate and the wire. The voltage applied to the two electrodes was produced by alternating current power supplies. For high frequency, a 2.55 megacycle source capable of delivering 200 volts r.m.s. was used, and for low frequencies the power supply consisted of a Hewlett Packard 200 CD audio oscillator and a Heath A9 audio amplifier. The voltmeter was a Hewlett 410 A radio frequency voltmeter which had a frequency range capability from 20 cycles per second to 200 megacycles per second. A circuit diagram showing the electrical arrangements is shown in Figure 6.

A mixed bed ion-exchange column was constructed to obtain highly deionized water. Freshly deionized water was obtained with resistivity in the order of 10^7 ohm-cm or more. Solutions of salts were made from 10^{-2} N to 10^{-7} N, with resistivity ranging from 10^3 to 10^6 ohm-cm, and were stored in 500 ml liter bottles with ground glass stoppers.

Procedure

Six crystals of wide range of dielectric constants and resistivities were used. A table of the names and values can be found on Table I.

Salt solutions of different cation and anion valencies and a wide range of concentrations of each were introduced. The following salts were studied: K^+, Ca^{++}, La^{+++}, and Th^{++++} as nitrates, and K_2SO_4.

TABLE I

PHYSICAL PROPERTIES OF CRYSTALS

Substance	Resistivity	Reference Source	Dielectric Constant	Frequency	Reference Sources
Lead hafnate	10^{16} ohm-cm	F	350	1 MHz	A
Quartz	10^{18} ohm-cm	D	3.78	1 MHz	B
Silicon	5×10^{4} ohm-cm	F	11.7	13 GM	C
Stannic oxide	2.7×10^{5} ohm-cm	A	24.0	1 MHz	A
Sn	10^{-5} ohm-cm	D	20-30	1 MHz	D
TiO_2	10^{12} ohm-cm	E	$\perp 86$ $// 170$	1 MHz	B

A - Dr. E. E. Kohnke, Okla. State University, private communication.

B - Von Hippel, *Dielectric Materials and Applications*, published jointly by Tech. Press of M.I.T. and John Wiley and Sons, Inc., New York (1954).

C - H. B. Briggs, Phys. Rev., *77*, 287 (1950).

D - *Handbook of Chemistry and Physics*, published by Chemical Rubber Co., 44th ed.

E - D. C. Cronimeyer, Phys. Rev., *87*, 896 (1951).

F - Measured in our laboratory.

They were used in concentration of 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6}, 10^{-7} molar.

Each solution was introduced into the circulatory system from the bottles by air pressure. Starting with low resistivity (high concentration) for each salt solution and going up, tables of deflection versus voltage for each solution were recorded. From this data, a family of deflection versus voltage-squared curves were obtained. Another set of curves would like-wise be obtained for a different frequency. Initial slopes of these curves were plotted against the voltage squared for comparison of the effects at different frequencies. The graphs are shown in Chapter IV and the discussion of them is given in Chapter V.

CHAPTER IV

RESULTS

Curves of deflection versus voltage squared for lead hafnate, silicon, tin, silicon oxide, quartz and rutile were drawn. Each crystal has a set of five curves for each frequency for the five salt solutions used. Three different frequencies were used: 1 K Hz., 20 K Hz. and 2.55 M Hz. A typical graph showing deflection and voltage squared is shown in Figure 7.

The initial slopes of all these curves were plotted against the resistivity of the medium as shown from Figures 8-25. Positive slope denotes motion toward the region of higher field intensity, and negative slope denotes motion toward the region of lower field intensity.

It is observed that $PbHfO_3$ with dielectric constant 350 moves in the positive direction for 2.55 M Hz., see Figure 8, as predicted by equation (1) in Chapter I; but for 20 K Hz., it crosses the zero slope line and the deflection becomes negative as the resistivity of the medium becomes lower, see Figure 9; and for 1 K Hz., the deflections are always negative for all resistivities, see Figure 10.

It is also observed in Figure 8 that for cations of different valencies, the slope curves, in the resistivity range 5 x 10^4 ohm-cm. to 10^7 ohm-cm., show increasing slope values with increase of ion valency.

For SnO_2 crystal, all deflections were negative; ions show similar

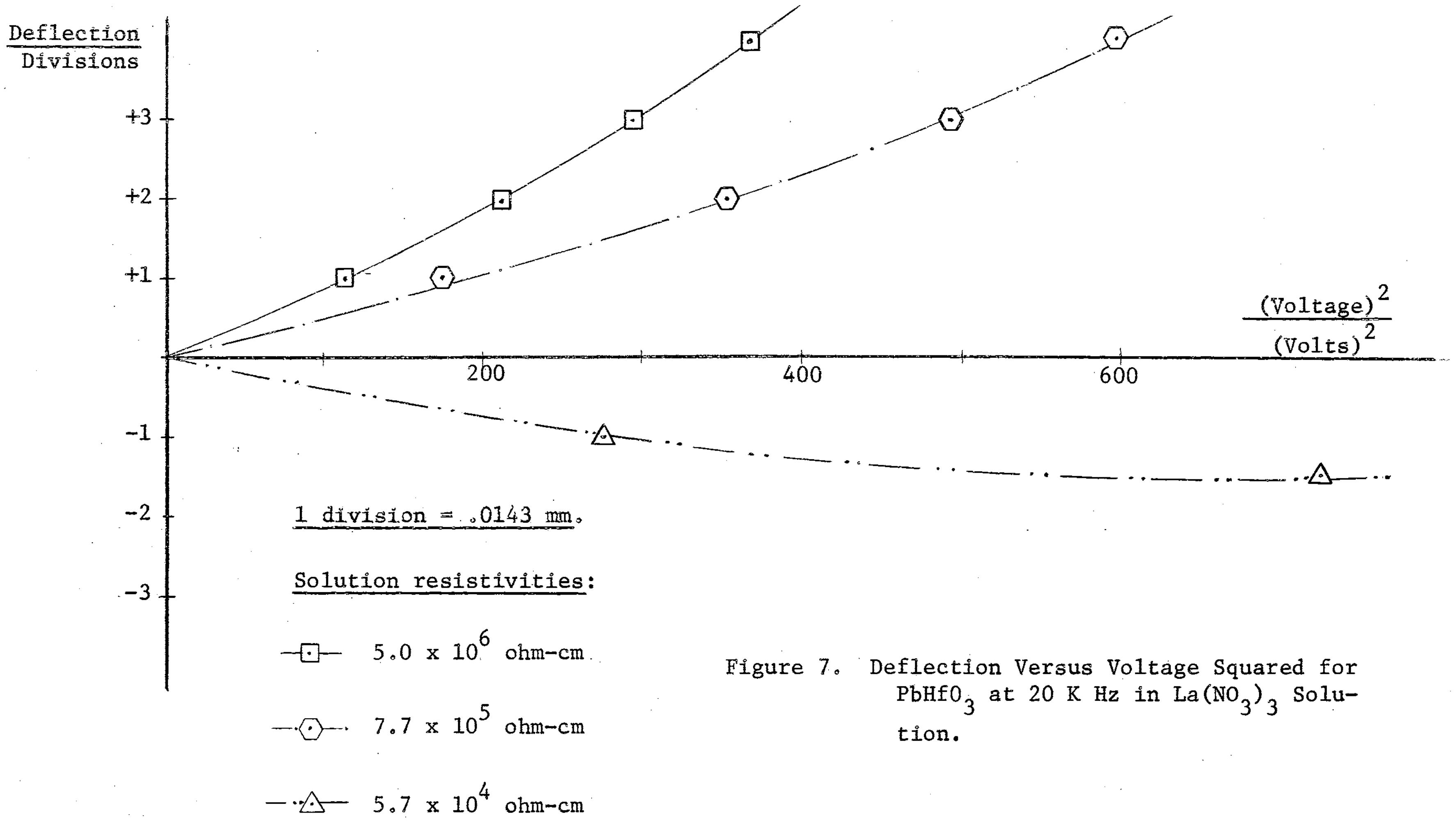


Figure 7. Deflection Versus Voltage Squared for $PbHfO_3$ at 20 K Hz in $La(NO_3)_3$ Solution.

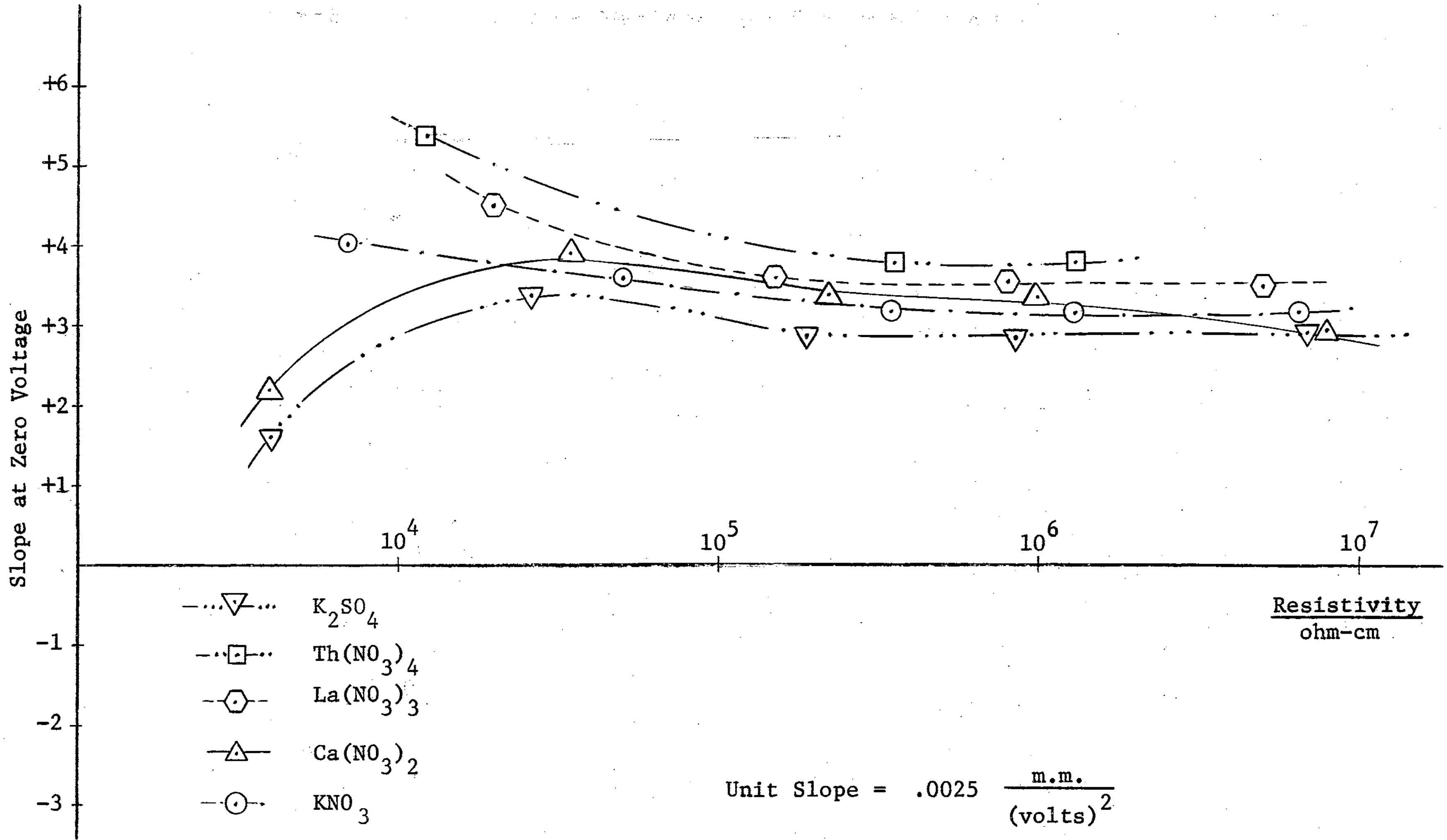


Figure 8. Initial Slope Versus Resistivity of Solutions for $PbHfO_3$ at 2.55 MHz

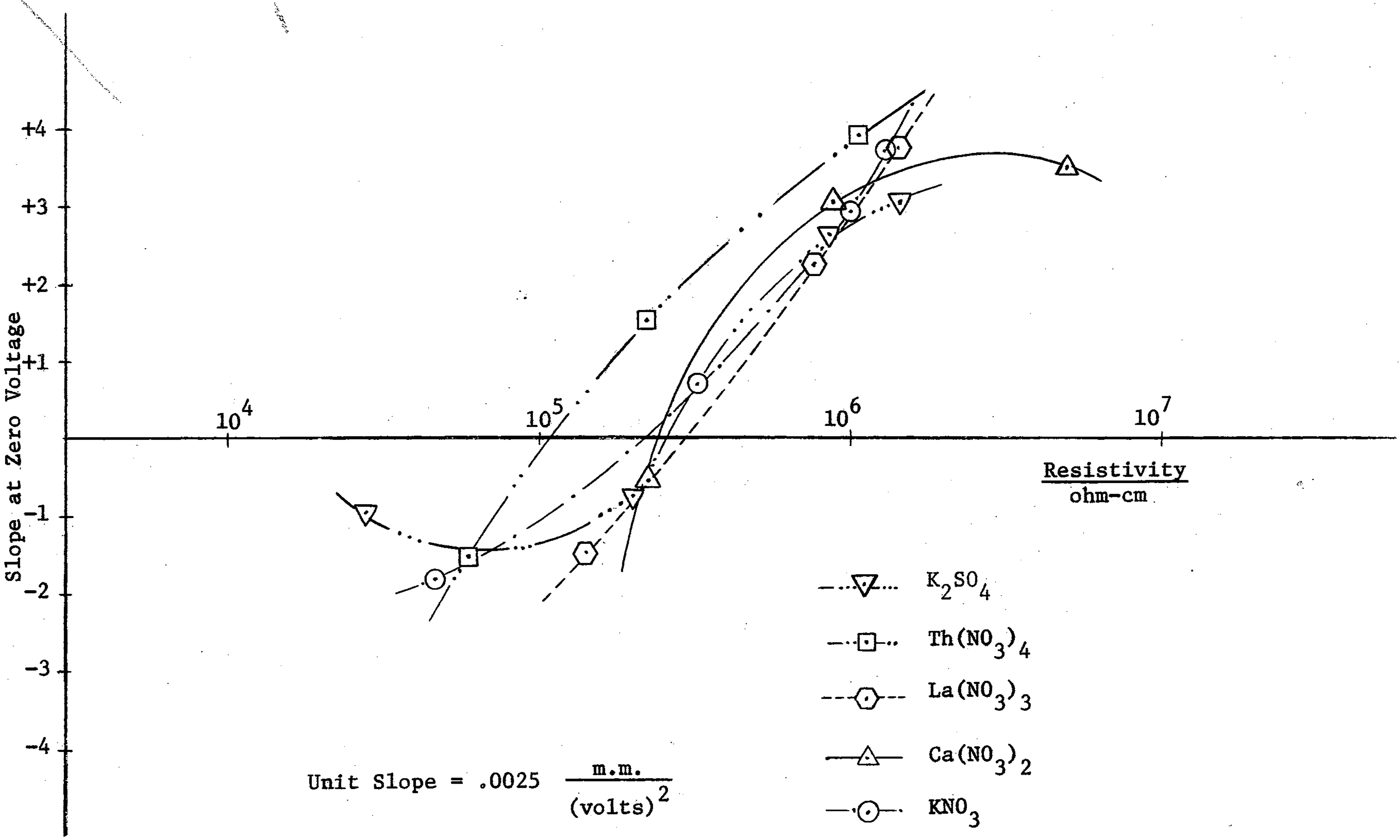


Figure 9. Initial Slope Versus Resistivity of Solutions for $PbHfO_3$ at 20 K Hz

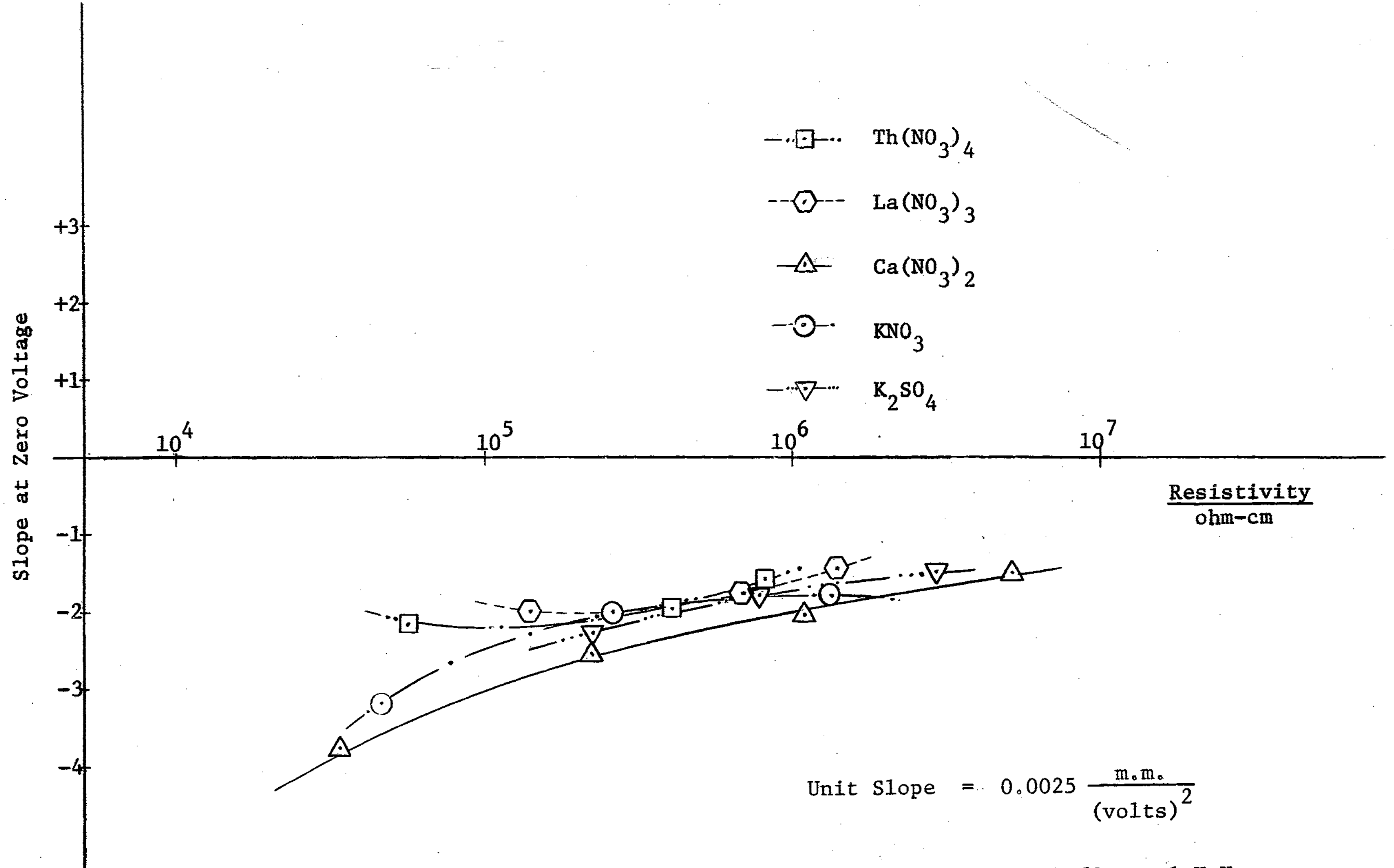


Figure 10. Initial Slope Versus Resistivity of Solutions for $PbHfO_3$ at 1 K Hz

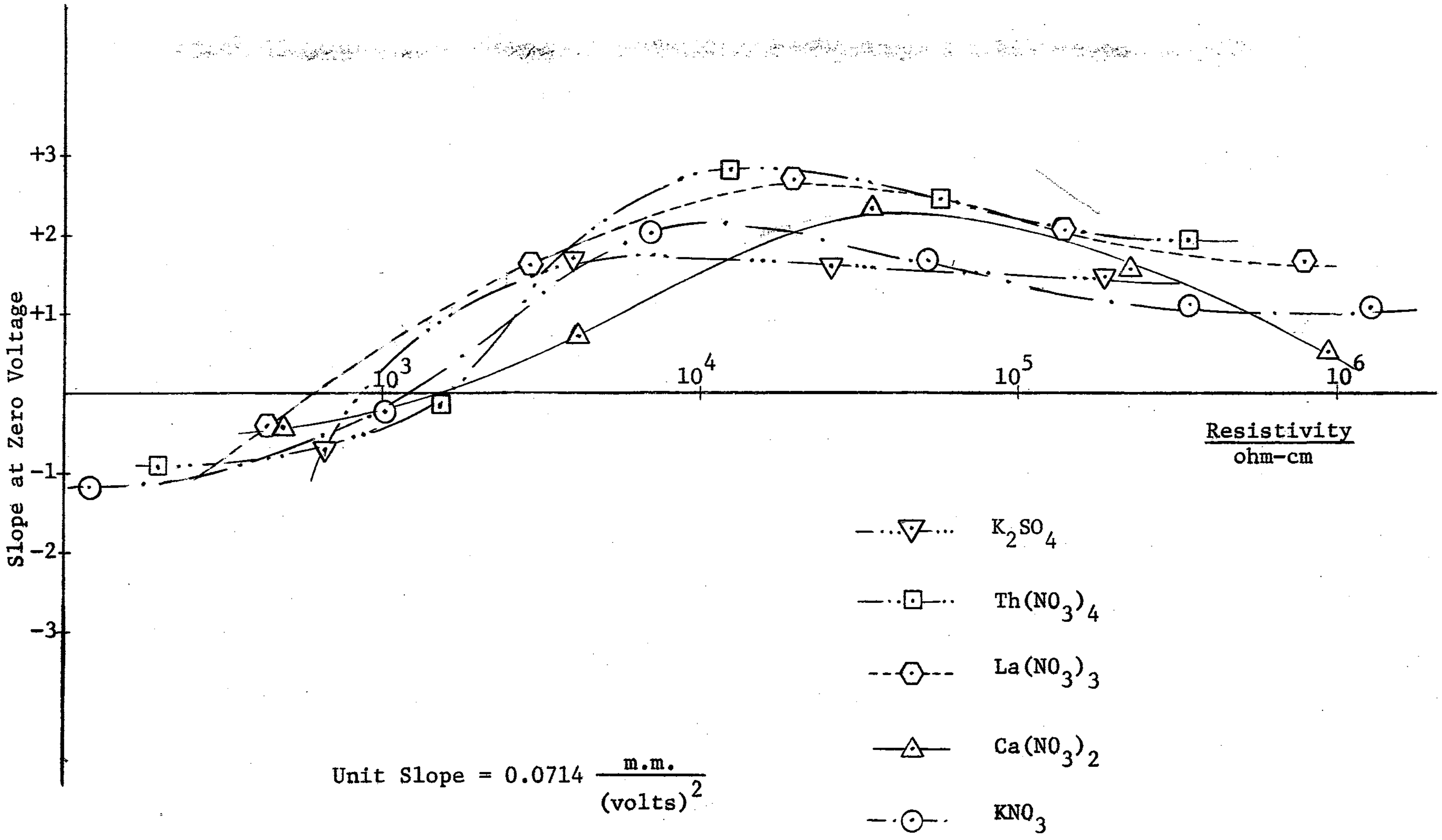


Figure 11. Initial Slope Versus Resistivity of Solutions for Silicon at 2.55 M Hz

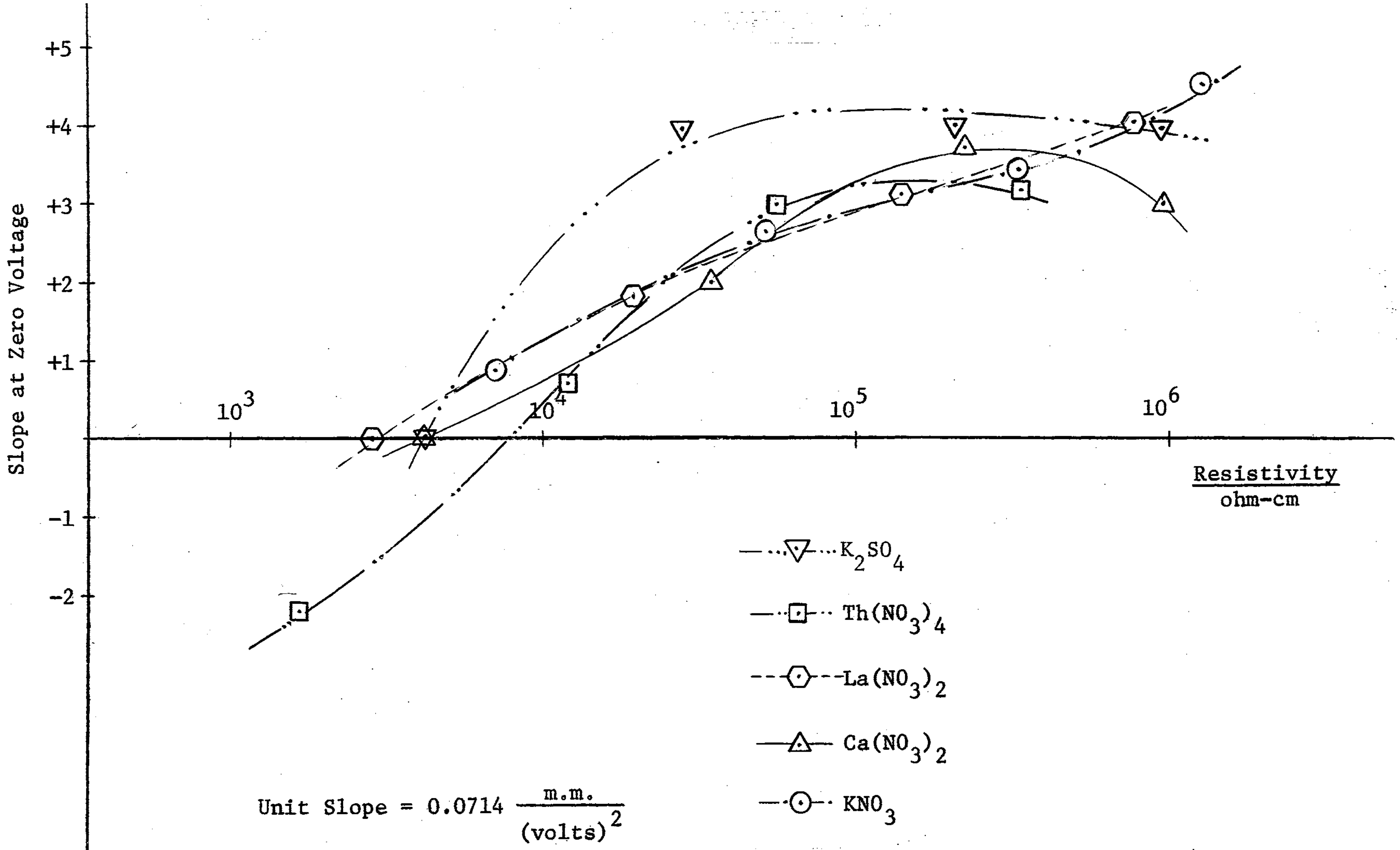


Figure 12. Initial Slope Versus Resistivity of Solutions for Silicon at 20 K Hz

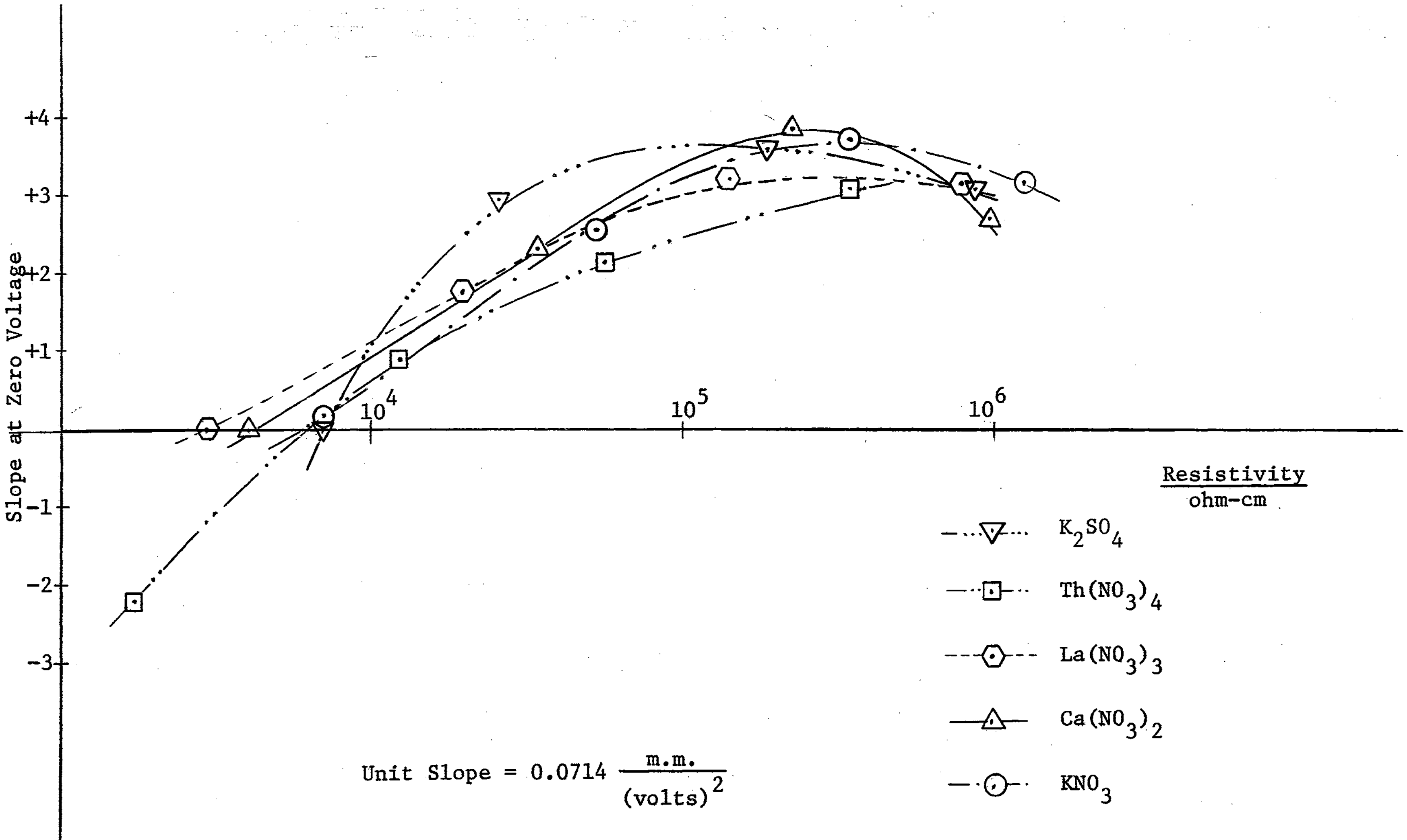


Figure 13. Initial Slope Versus Resistivity of Solutions for Silicon at 1 K Hz

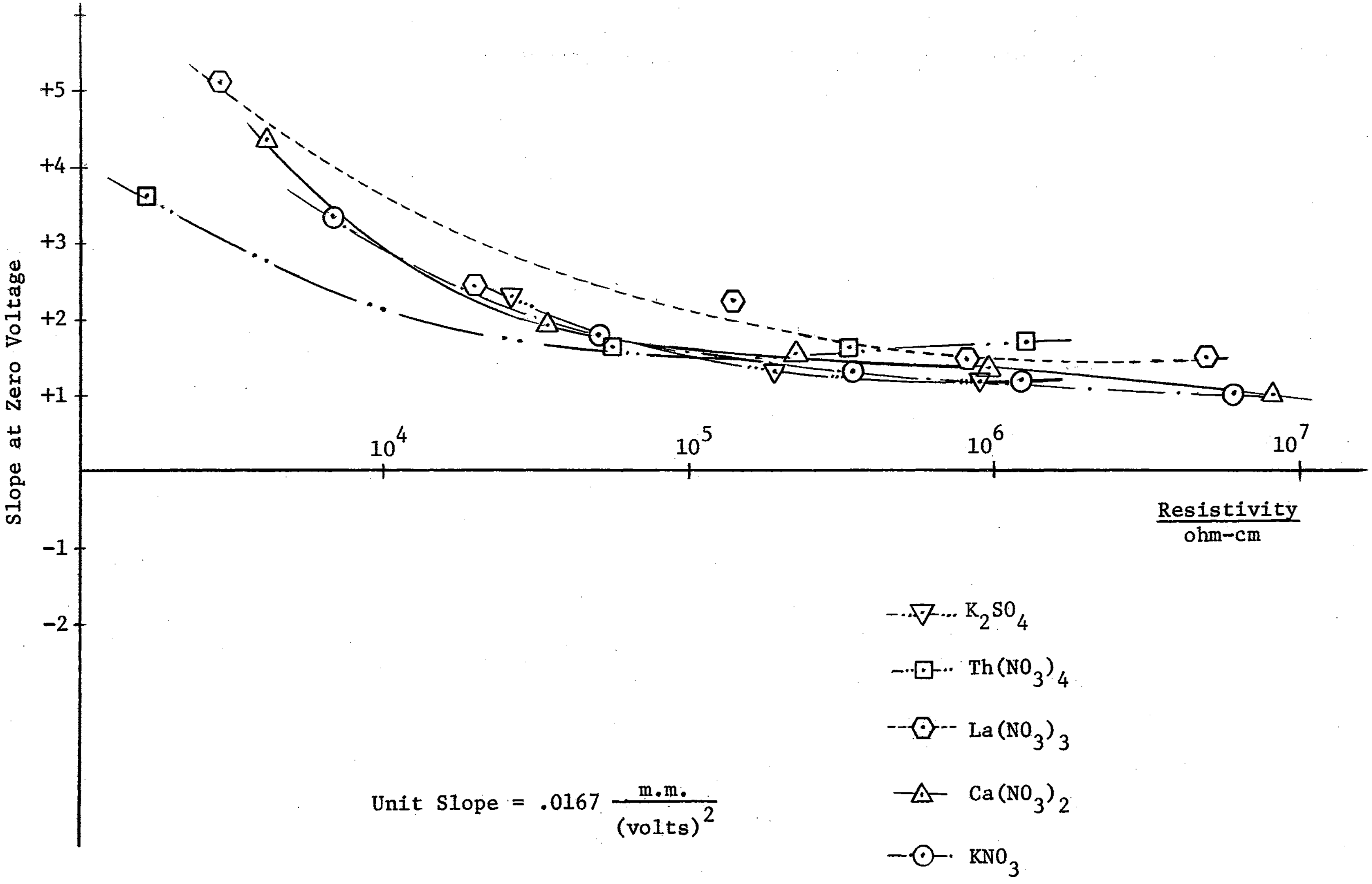


Figure 14. Initial Slope Versus Resistivity of Solutions for Tin at 2.55 MHz

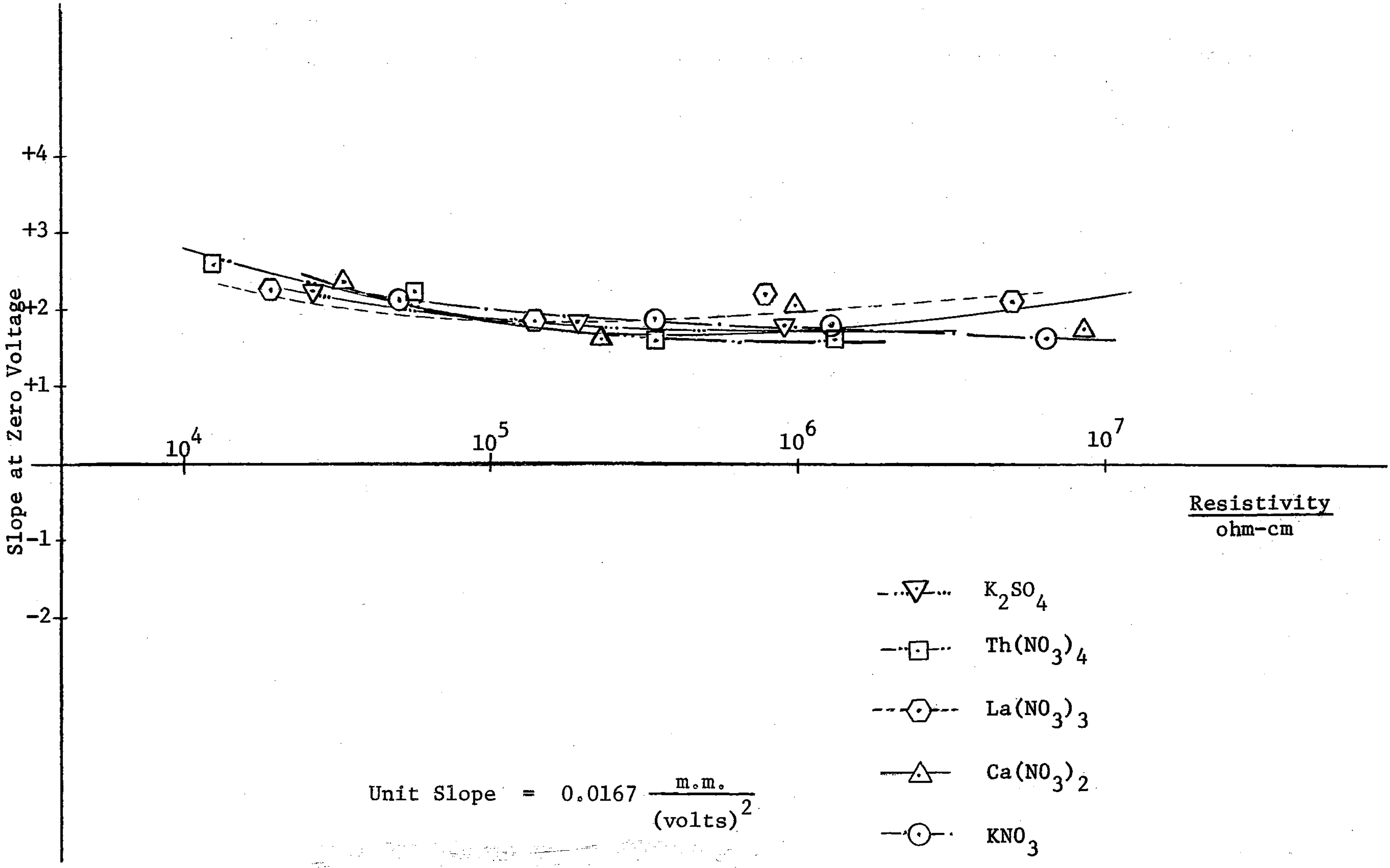


Figure 15. Initial Slope Versus Resistivity of Solutions for Tin at 20 K Hz

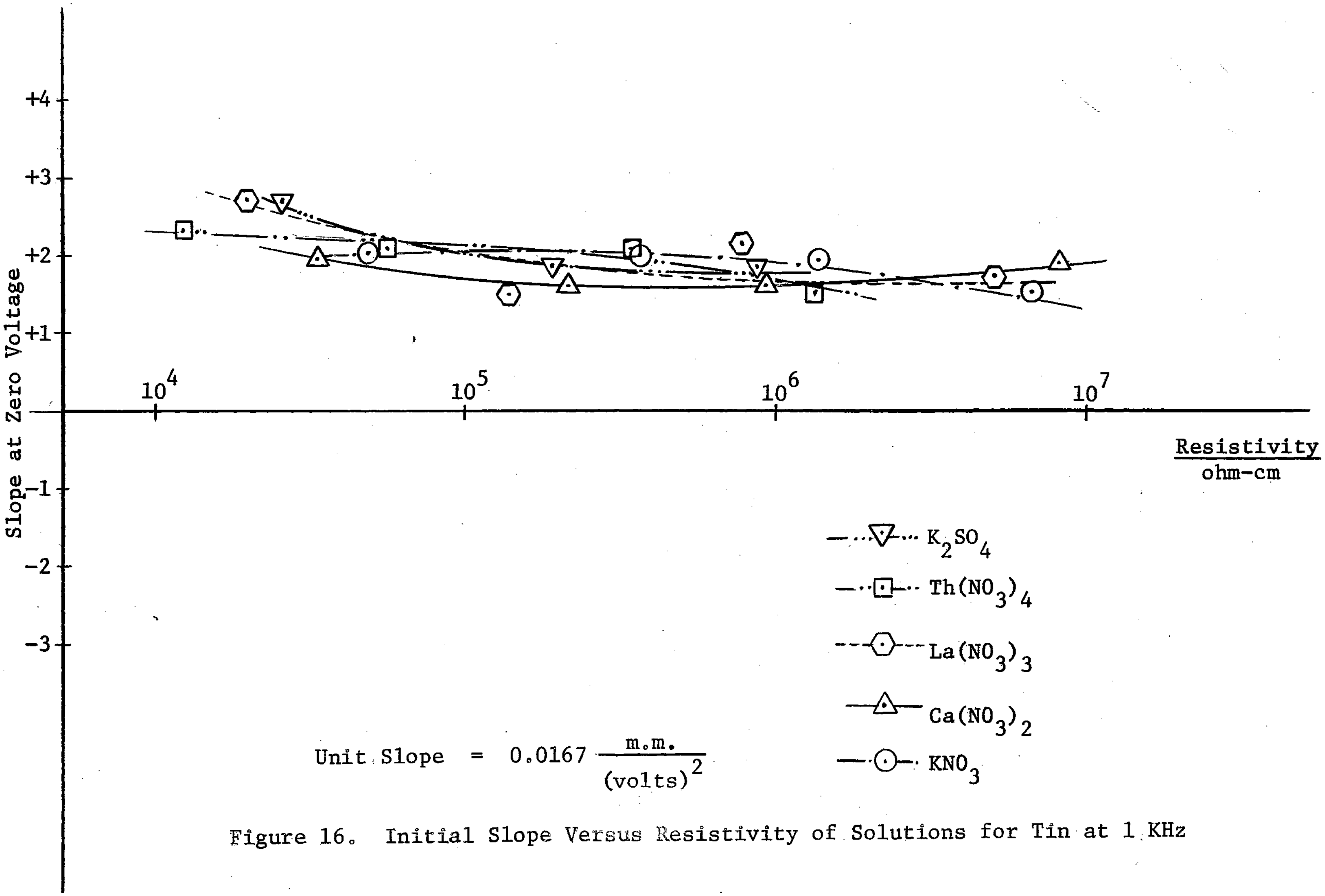


Figure 16. Initial Slope Versus Resistivity of Solutions for Tin at 1 KHz

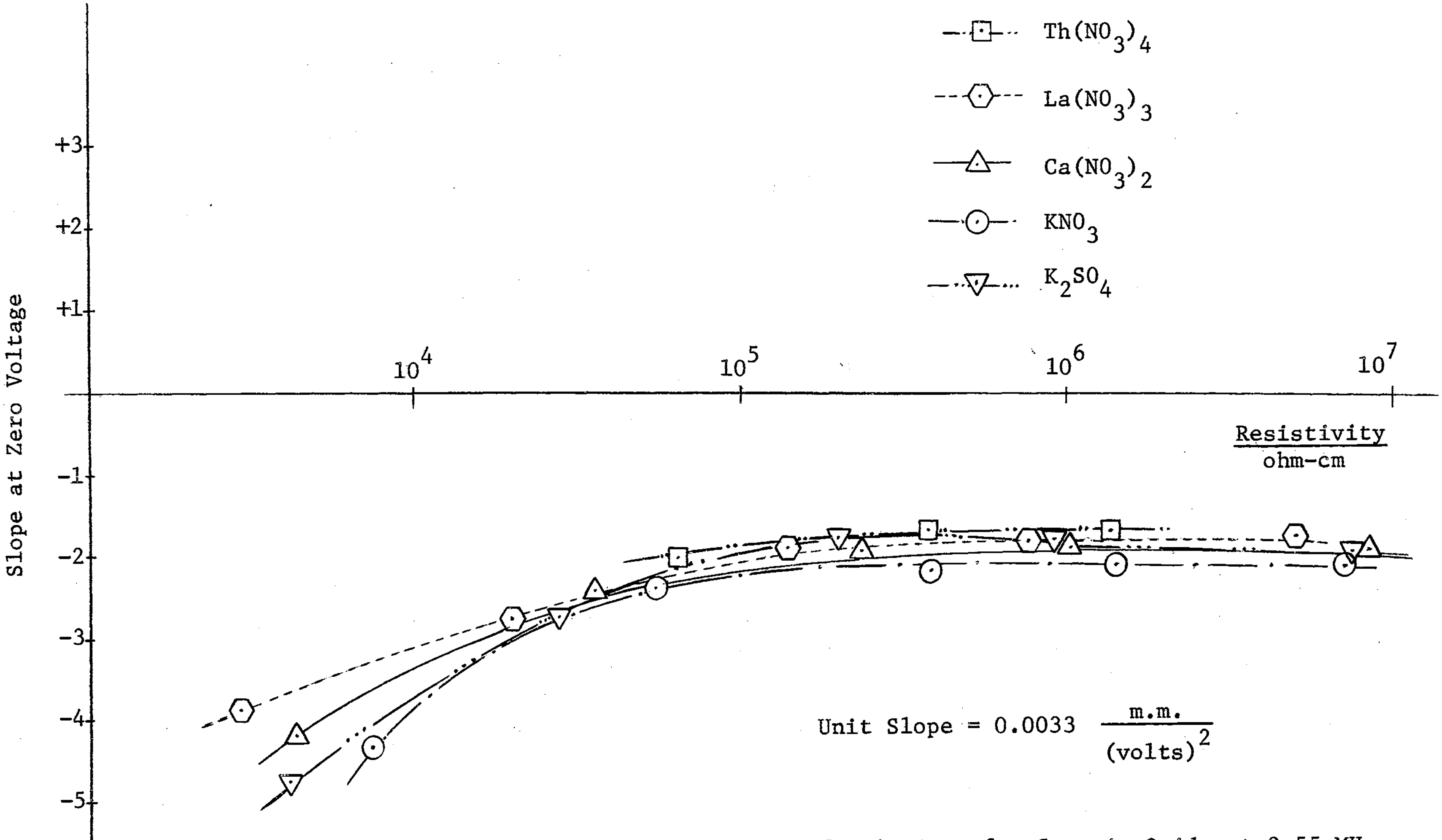


Figure 17. Initial Slope Versus Resistivity of Solutions for Stannic Oxide at 2.55 MHz

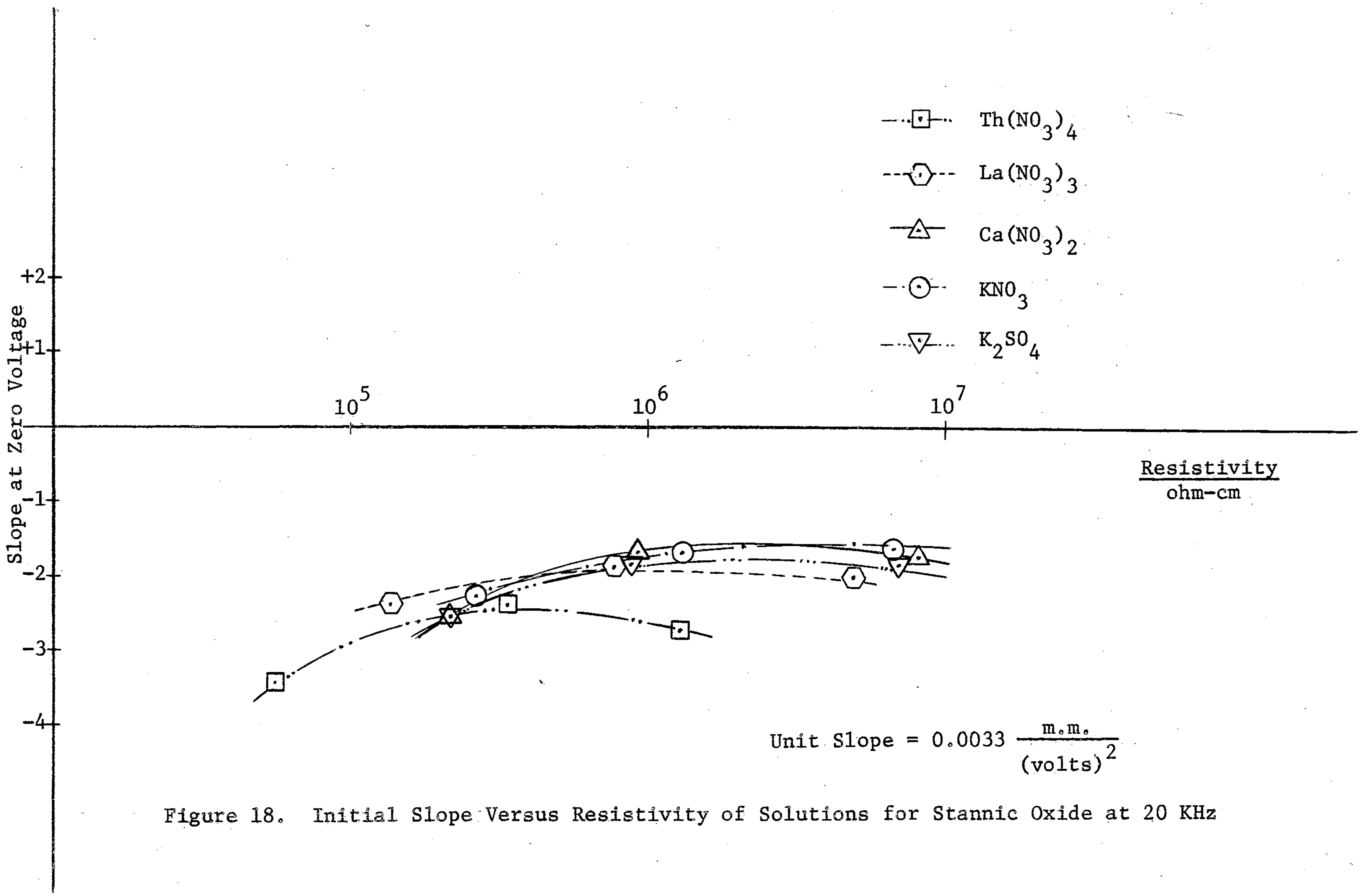


Figure 18. Initial Slope Versus Resistivity of Solutions for Stannic Oxide at 20 KHz

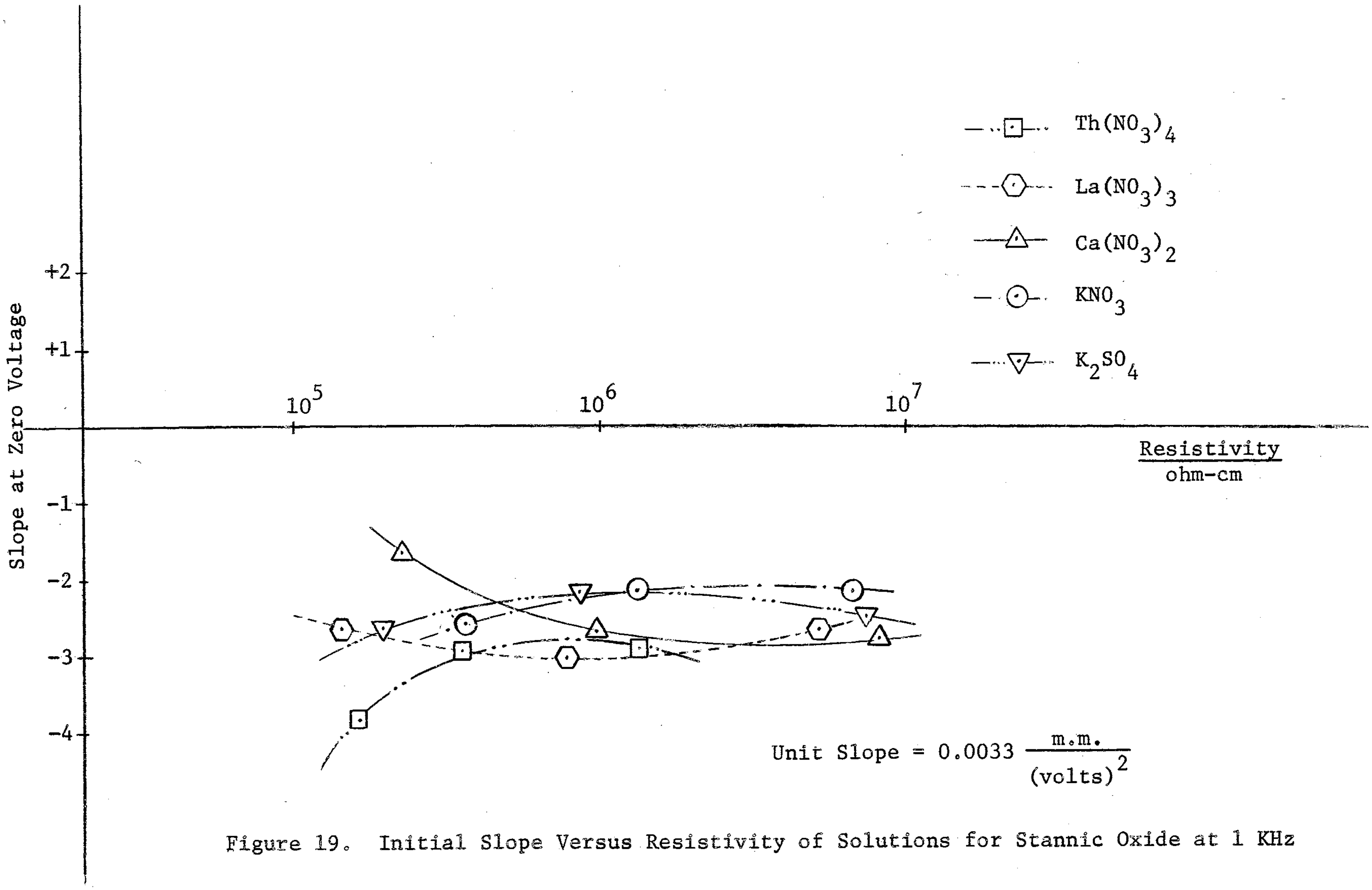


Figure 19. Initial Slope Versus Resistivity of Solutions for Stannic Oxide at 1 KHz

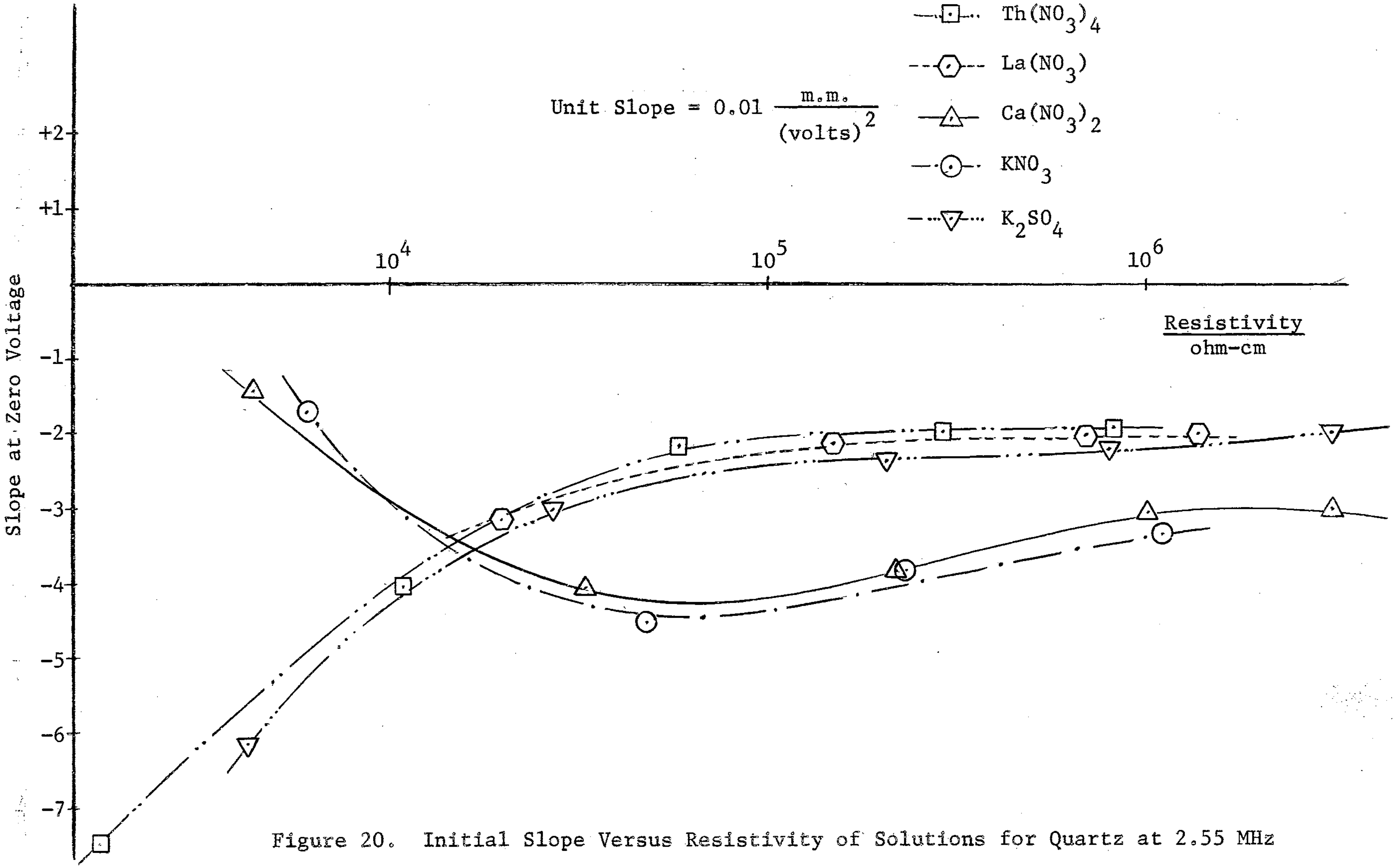


Figure 20. Initial Slope Versus Resistivity of Solutions for Quartz at 2.55 MHz

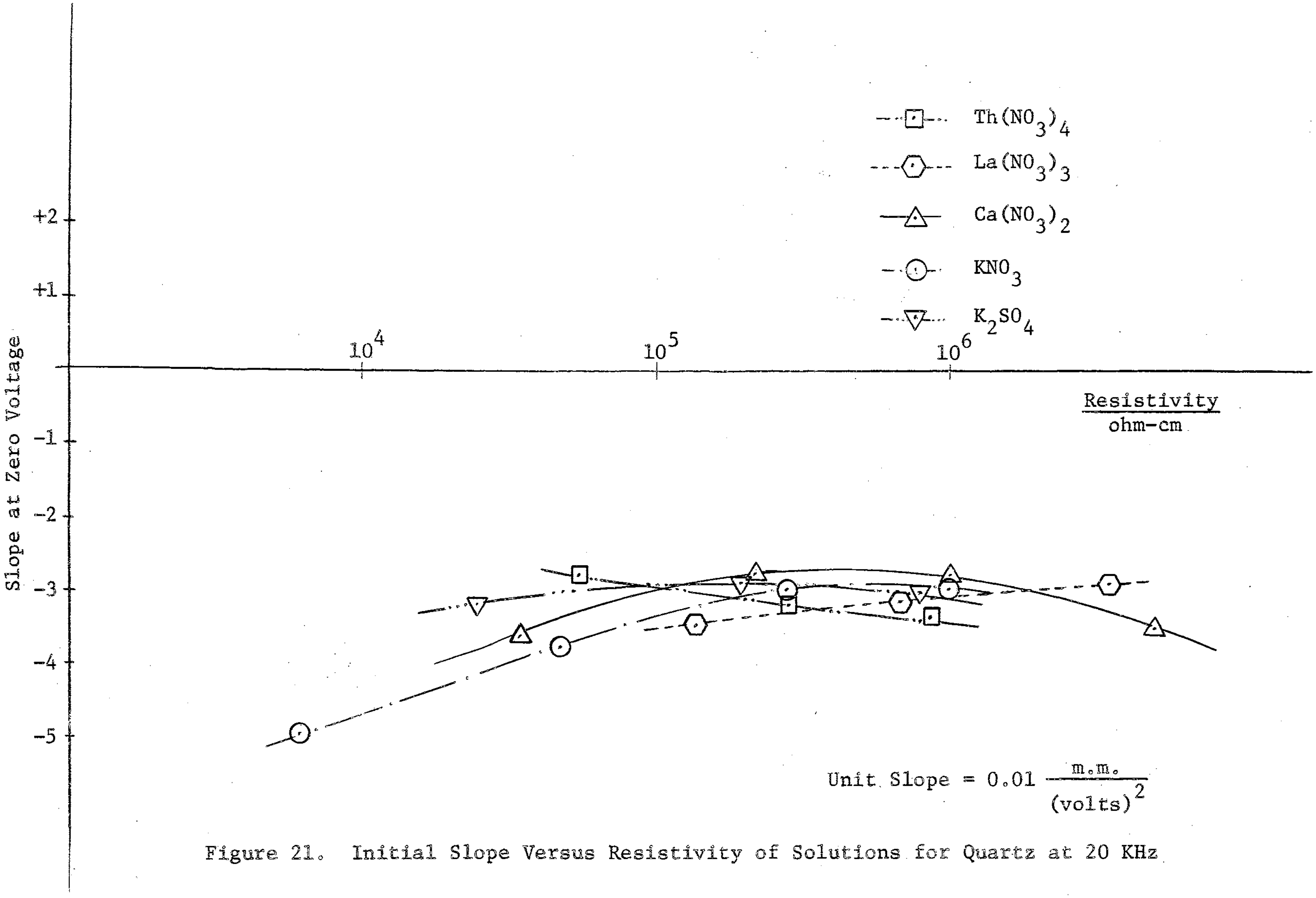


Figure 21. Initial Slope Versus Resistivity of Solutions for Quartz at 20 KHz

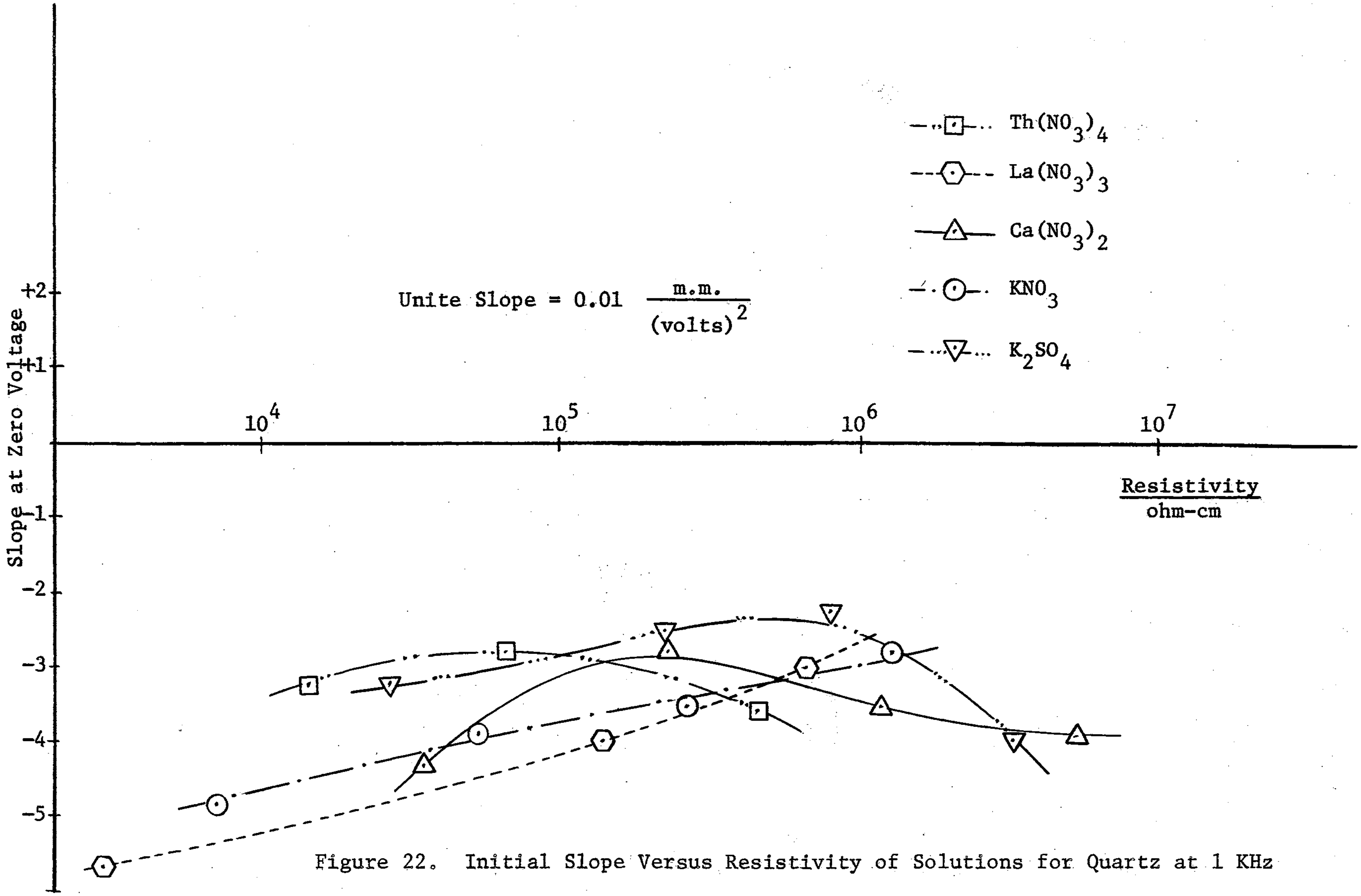


Figure 22. Initial Slope Versus Resistivity of Solutions for Quartz at 1 KHz

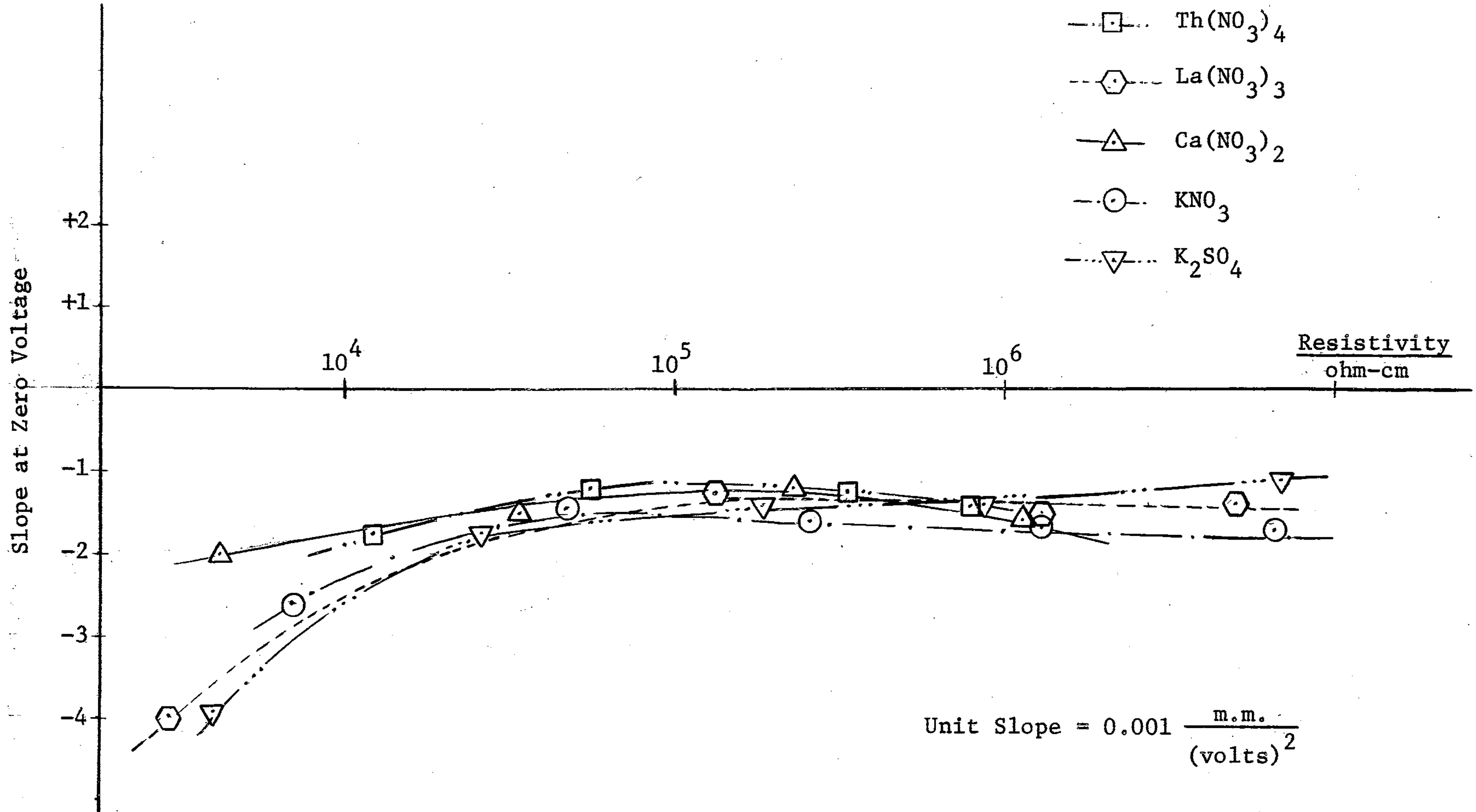


Figure 23. Initial Slope Versus Resistivity of Solutions for Rutile at 2.55 MHz

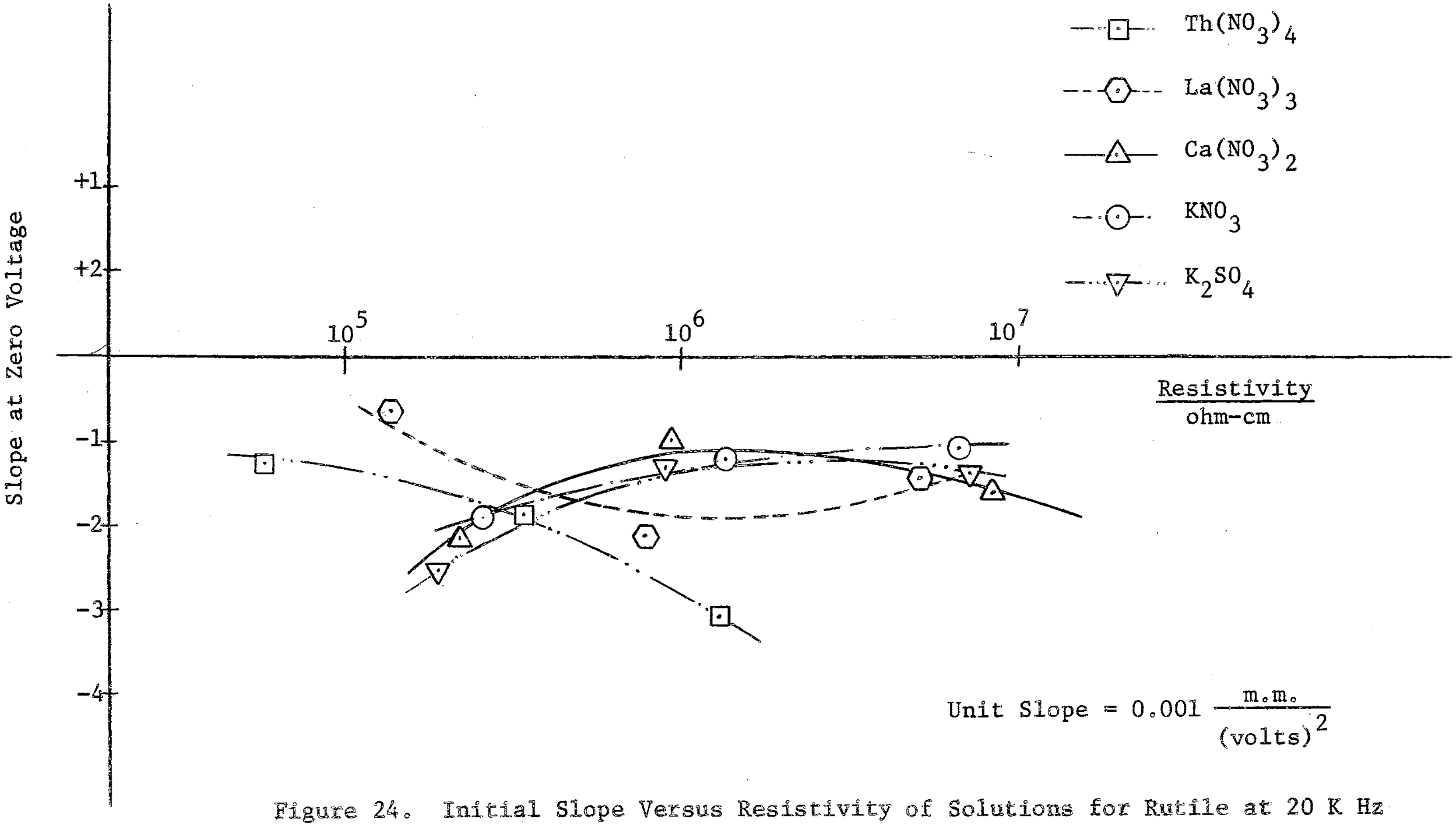


Figure 24. Initial Slope Versus Resistivity of Solutions for Rutile at 20 K Hz

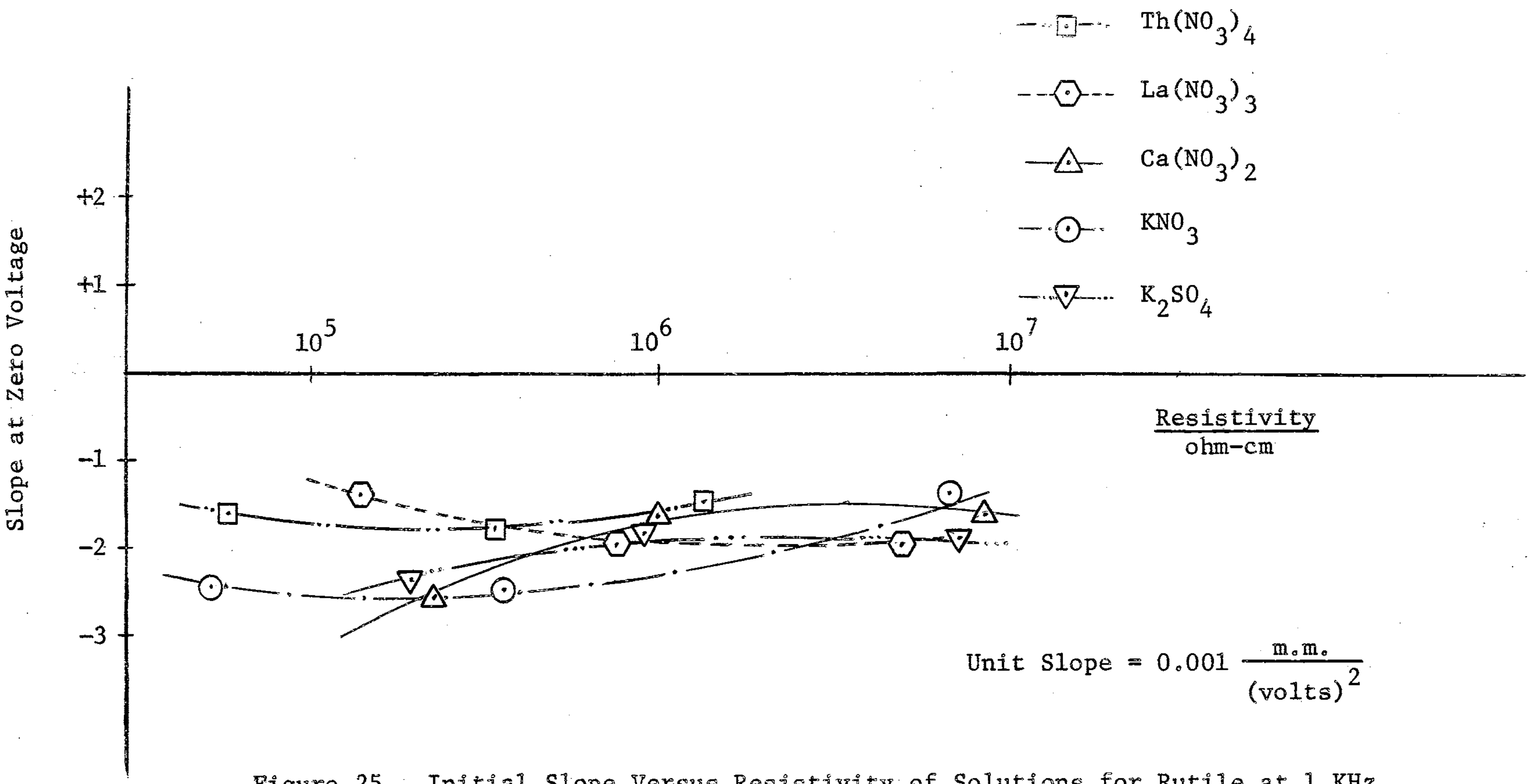


Figure 25. Initial Slope Versus Resistivity of Solutions for Rutile at 1 KHz

order as in Figure 8 for 2.55 M Hz., see Figure 17.

For quartz, all deflections were negative; ions show similar order as in Figure 8 for 2.55 M Hz., see Figure 20.

For rutile, all deflections were negative and little relation between ions and slopes were shown. (Compare, however, Figures 23-25 with Hawk's results on rutile, Figure 14, his thesis.)

In view of the fact that some crystals have a crossover point or zero slope on the slope versus resistivity graph and some have not, an attempt has been made to correlate this with theory[1]. According to Sher's equation of force[5]: (See Chapter II).

$$\vec{F} = \frac{3}{2} V_1 \,\mathrm{Re} \left(\frac{\widetilde{\varepsilon_1^*} \, (\varepsilon_2^* - \varepsilon_1^*)}{\varepsilon_2^* + 2\varepsilon_1^*} \right) \vec{\nabla} \, (\varepsilon_o^{\,2})$$

Now, for zero slope of displacement, the force on the sphere should be zero, this implies

$$\mathrm{Re} \left\{ \frac{\widetilde{K_1^*} \, (K_2^* - K_1^*)}{K_2^* + 2K_1^*} \right\} = 0$$

or

$$K_1 \, [K_2^{\,2} + K_1 K_2 - 2K_1^{\,2} + S_2^{\,2} + 4S_1 S_2 - 2S_1^{\,2}] - 3K_2 S_1^{\,2} = 0$$

where

$$S_i = \frac{1}{\rho_i \omega \varepsilon_0} = \frac{1}{\rho_i 2\pi\nu\varepsilon_0}$$

$$\omega = 2\pi\nu$$

$$\varepsilon_0 = \frac{1}{36\pi \times 10^9}$$

$$\varepsilon_j = \varepsilon_j' - i\varepsilon_j'' = \varepsilon_j' - i\,\frac{\sigma_j}{\omega} = \varepsilon_j' - i\,\frac{\sigma_j}{\omega} = \varepsilon_j' - \frac{i}{\rho_j \omega} = \varepsilon_o K_j^*$$

The actual zero slope of resistivity for $PbHfO_3$ and Si crystals for various frequencies were used to check against this equation. (See Appendix for program and results.) Unfortunately, they did not seem to agree.

A graphical method is also suggested to check the crossover point, and also the positive and negative slopes. When the force on the particle is zero, the value $\left| K_1' - \frac{i}{\rho_1 \omega \varepsilon_o} \right|$ is equal to $\left| K_2' - \frac{i}{\rho_2 \omega \varepsilon_o} \right|$.

If one plots $A^{\frac{1}{2}} = \sqrt{K^2 + S^2}$, where $S = \sqrt{\frac{1}{\rho^2 \omega^2 \varepsilon_o^2}}$, versus the frequency, the position where $A_1^{\frac{1}{2}}$ and $A_2^{\frac{1}{2}}$ curves intersect should correspond to the value of the zero slope. In Figure 26, the $A^{\frac{1}{2}}$ curves for salt solutions of resistivity ranging from 10 ohm-cm to 10^5 ohm-cm and the $A^{\frac{1}{2}}$'s of crystals of a wide range of dielectric constants, $PbHfO_3$ (350), Si (11.7), SnO_2 (24) and SiO_2 (3.78) were plotted.

The $A^{\frac{1}{2}}$ curve for $PbHfO_3$, for 20 K Hz, the zero slope occur somewhere between 10^5 to 10^6 ohm-cm. As the resistivity becomes higher, the slope should be positive, because $A^{\frac{1}{2}}$ for $PbHfO_3$ is greater than that of the solution. For 2.55 M Hz., the zero slope should occur between 10^3 to 10^4 ohm-cm. Resistivities greater than that value should have positive slopes, and less than that value should have negative slopes. For 1 K Hz., solution resistivity in the neighborhood of 5×10^6 ohm-cm should have zero slope, and lower resistivities should have negative slopes. These all seem to correspond to the experimental data quite well. (See Figures 8-10.)

$$A^{\frac{1}{2}} = \sqrt{K^2 + S^2}$$

$$S = \frac{1}{\rho\omega\varepsilon_o} = \frac{1}{2\pi\varepsilon_o\rho f}$$

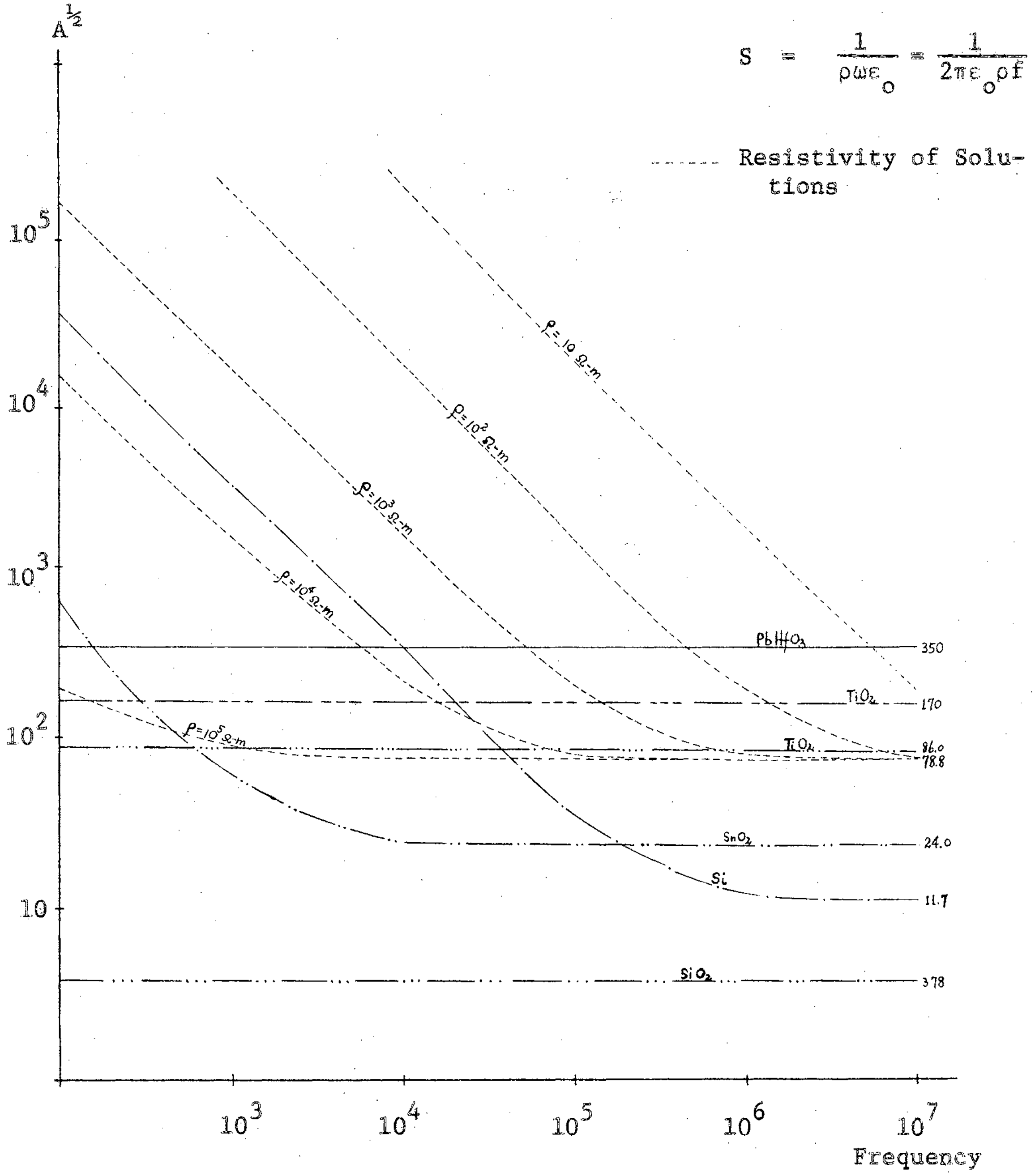


Figure 26. Graph of $A^{\frac{1}{2}}$ Versus Frequency

For Si, the zero points do not correspond to the experimental values in Figures 11-13.

For SnO_2, Figure 26 shows that the deflection should always be negative for all frequencies and this seems to be in good agreement with the experimental data shown in Figures 17-19. The same applies to SiO_2.

CHAPTER V

SUMMARY

We have made a systematic investigation of the effect of ions on dielectrophoresis. From the results shown in Chapter IV, particularly Figure 8 and Figure 20, it is obvious that cations with different valencies do have different effects. Therefore, one can conclude qualitatively that an electrical double layer which affects dielectrophoresis does exist at the solid-liquid interface.

We observe that the effect on dielectrophoresis differs according to the ionic valency. This difference is most clearly shown at the highest frequency (2.55 M Hz) and in the most dilute solutions. High ionic strength appears to repress the effect. It is also less visible at low frequencies (1 and 20 K Hz).

The differences in dielectrophoretic force caused by the nitrate salts of mono-, di-, tri- and tetra-valent cations are most strikingly shown on $PbHfO_3$ and on SiO_2. A lesser effect is, however, still visible on Si, SnO_2, TiO_2 and Sn.

From the fact that this ionic valence effect is only observable at extremely high frequencies (2.55 M Hz), one is led to conclude that the effect of the double layer is accounted for totally at the polarization or real part of curves such as in Figure 26 rather than the conduction part of the dielectric constant in the complex expression $K^* = K' - i\frac{1}{\rho\omega\varepsilon_o}$.

If one hypothesizes that this is true, then the anomalous behaviour of Si having positive deflections can easily be explained, because if K' is increased by the double layer, the whole of the $A^{\frac{1}{2}}$ (effective polarization) curve would be raised (see Figure 26). If it is raised to a value higher than that of water, the deflections will be predicted to be positive by Figure 26. There is little rigorous mathematical background to this, but this does give a suggestion for the explanation of the anomalous effects of dielectrophoresis.

An alternate view or interpretation might be offered in terms of interfacial or Maxwell-Wagner polarization. Taking the case of the semiconductor, silicon, for example, we note that the preferential sorption of OH^- ions on the surface would modify the surface states and bend up the valence and conduction bands at the crystal edge. This means attracting holes to the crystal face and pushing electronic carriers to the crystal center. Now let us look at the effect of an externally applied (a.c.) field.

When an external field is applied in the surrounding liquid medium, the sorbed OH^- layer will be built up on the side of the crystal toward the (negative) cathode and will be depleted of OH^- ions on the side toward the (positive) anode. This will in turn cause a shift in the internal hole and electron surface states of the crystal, with a concommitant shift in polarization within the crystal. The degree and rate of shift will depend upon the carrier mobilities, upon their concentrations, and upon the surface state concentrations. This enhanced interfacial polarization would therefore be most evident at low frequencies and least efficient at high frequencies, would be most evident if hole and electron carriers are freely present, and be least evident in solids lacking such free carriers. The interfacial polarization within the semiconductor, and appearing at the Schottky barriers could be intense enough to give the Si crystal an effective polarizability larger than that of the aqueous medium. If so, then the Si crystal could easily show a positive deflection (i.e. behave as if it were more polarizable than the aqueous medium) in dielectrophoresis at low frequencies--and show a negative deflection at high frequencies. Since this is just what is observed experimentally, we suggest then that Maxwell-Wagner or interfacial polarization associated with Schottky barriers modified by sorbed ions can well be the logical molecular explanation for the otherwise anomalous dielectrophoretic behavior of pure silicon single crystal in aqueous solutions.

It would appear that all the dielectrophoretic crystals examined here have very different surface properties. This is obvious in Figures 8-25. Roughly speaking, the ionic valence effect is seen to be greatest in those materials with the highest resistivity, and vice versa.

Such might well be expected if one considers that the more conductive materials would be more capable of supplying internal charges mobile enough and numerous enough to counteract the surface double layer charges caused by the variously sorbed ions, that is, internal conduction suppresses surface double layer effects on dielectrophoresis. Double layer effects by cations of varied valence in dielectrophoresis are therefore best to be seen on the more insulating materials.

Further research must be done before the exact effect of the ions in dielectrophoresis could be clearly understood. Redesigning of the present apparatus of investigation is a necessary next step, since the size of the crystal, smoothness of the crystal surface and the attachment of the glass fiber are probably major sources of errors in this research.

BIBLIOGRAPHY

1. Pohl, H. A., J. Appl. Phys., 29, 1182 (1958).

2. Pohl, H. A., and J. P. Schwar, J. Appl. Phys., 30, 69 (1959).

3. Hawk, I., H. D. Crawford, R. F. Davidson, and H. A. Pohl. "The Behavior of Conductive Dielectrics in Non-Uniform Electric Fields". (To be published.)

4. Glasstone, S., "Text Book of Physical Chemistry". Chapter XIV.

5. Sher, L. D., Nature 220, 695 (1968).

APPENDIX

```
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       200 READ(5,100)B,F,C,D
       100 FORMAT(4E16.8)
            I=I+1
            A=78.5
            E=8.85*10.0**(-12)
            S=1.0/(2.0*3.14159*F*E*C)
            R=1.0/(2.0*3.14159*F*E*D)
             Z=(A*(B**2+A*B+R**2+4.0*S*R-2.0*A**2-2.0*S**2)-(3.0*B*S**2))/
           1((B+2.0*A)**2+(R+2.0*S)**2)
            WRITE (6,10) B,F,C,D,S,R,Z
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           1' S1=',E12.5,' S2=',E12.5,' ZZ=',E12.5)
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            END

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VITA

Katherine Wei-lan Loo Chen

Candidate for the Degree of

Master of Science

Thesis: DIELECTROPHORESIS OF SOLIDS IN AQUEOUS SOLUTIONS

Major Field: Physics

Biographical:

Personal Data: Born in Shanghai, China, July 2, 1941, daughter of Chieu Wan-Yu and Y. T. Loo.

Education: Attended secondary school in Hong Kong, and graduated from Dioceson Girls' School in 1961; attended Chung Chi College in Hong Kong; received Bachelor of Science degree from Sam Houston State College, Huntsville, Texas, with a major in physics in May, 1967.

Organizations: A member of Sigma Pi Sigma, Physics Honor Society.